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AN INVESTIGATION OF A PROTOTYPE OASYS' EFFECTIVENESS IN MANEUVERING FLIGHT

by

Christopher Cyril Sullivan

September 1992

Thesis Advisor: Dr. E. Roberts Wood

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AN ANALYSIS OF THE CURRENT NORTHROP HELICOPTER OBSTACLE AVOIDANCE SYSTEM (OASYS) PROTOTYPE WITH A FIXED FORWARD MOUNTING, 25 X 50 DEGREE FIELD OF VIEW, 860 NANOMETER WAVELENGTH LADAR, WAS CONDUCTED TO DETERMINE SYSTEM EFFECTIVENESS DURING SIMULATED AIRCRAFT LEVEL ACCELERATIONS RANGING FROM 0 TO 100 KNOTS, AND AT ACCELERATION RATES OF FROM 0 TO 2.9 METERS/SEC . COMPUTER SIMULATION FLIGHTS WERE CONDUCTED USING FLIGHT PARAMETER DATA RECORDED AT THE ARMY AEROFLIGHTDYNAMICS DIRECTORATE CREW STATION RESEARCH AND DEVELOPMENT FACILITY'S (CSRDF) ADVANCED CONCEPTS FLIGHT SIMULATOR. A MULTIPLE-PROGRAM COMPUTER SIMULATION WAS USED TO MODEL THE HELICOPTER AND SENSOR DYNAMICS OVER A TACTICAL DATA BASE OF NUMEROUS OBSTACLES CONSISTING OF TREES, WIRES, AND POLES; THE RESULTING WINDOW OF SAFETY (WOS) DISPLAYS WERE ANALYZED BY COMPARING EACH ACCELERATION MANEUVER WITH A CONTROL MANEUVER IN WHICH THE SENSOR WAS HORIZON STABILIZED. A MATHEMATICAL MODEL OF THE FLIGHT MANEUVERS FOR WHICH THE OASYS PROTOTYPE

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OPERATED EFFECTIVELY WAS THEN DETERMINED BASED ON THE RESULTS OF THESE SIMULATIONS. THE LIMITS OF THIS ANALYTICAL FLIGHT ENVELOPE WERE THEN VERIFIED EXPERIMENTALLY VIA A SERIES OF COMPUTER SIMULATIONS USING GENERALIZED MANEUVERS CONDUCTED OVER A STANDARDIZED OBSTACLE DATA BASE.

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An Investigation of a Prototype OASYS' Effectiveness in Maneuvering Flight

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

An analysis of the current Northrop helicopter obstacle avoidance system (OASYS) prototype with a fixed forward mounting, 25 x 50 degree field of view, 860 nanometer wavelength LADAR, was conducted to determine system effectiveness during simulated aircraft level accelerations ranging from 0 to 100 knots, and at acceleration rates of from 0 to 2.9 meters/sec^2. Computer simulation flights were conducted using flight parameter data recorded at the Army Aeroflightdynamics Directorate Crew Station Research and Development Facility's (CSRDF) advanced concepts flight simulator. A multiple-program computer simulation was used to model the helicopter and sensor dynamics over a tactical data base of numerous obstacles consisting of trees, wires, and poles; the resulting window of safety (WOS) displays were analyzed by comparing each acceleration maneuver with a control maneuver in which the sensor was horizon stabilized. A mathematical model of the flight maneuvers for which the OASYS prototype operated effectively was then determined based on the results of these simulations. The limits of this analytical flight envelope were then verified experimentally via a series of computer simulations using generalized maneuvers conducted over a standardized obstacle data base.

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Also, I would like to express my thanks to Mr. Carl Bose of BES, who taught me how the Northrop prototype OASYS works, guided me through each step of this research, and allowed me to use the computer simulation program which he developed to conduct this analysis. Without his help, this project would not have been possible.

I. INTRODUCTION

A. HISTORICAL BACKGROUND

In the 1970's, the US Army incorporated terrain flight into its tactical aviation missions. In this mode of flight, the crew workload is dramatically increased because of the need for the pilot to constantly adjust the flight controls to avoid obstacle contact. Workload increased even more so if the terrain flight were conducted at night with night vision goggles (NVG) because of the field of view, depth perception, and acuity limitations inherent in the goggles.

During the last several decades, hundreds of military aircraft and their crews have been lost due to obstacle contact during night terrain flight operations. Wires, poles, trees, and even the ground itself are the major contributors to the problem. Wires pose the greatest threat as they are extremely difficult to detect with the NVG (especially during periods of low moon illumination). Small trees and poles are also difficult to detect with NVG.

The ground itself may cause a problem during NVG terrain flight because of depth perception problems, especially if there are relatively few references in the field of view. This problem became especially acute during the 1990-91 Desert Shield and Desert Storm Operations, in which pilots were forced to fly their helicopters at relatively high airspeeds (on the order of 100 knots), at low altitudes (less than 100 feet AGL), over very flat terrain with few or no references. These conditions resulted in several mishaps as pilots unwittingly ran their aircraft into the desert floor.

A good deal of research has been conducted on the subject of obstacle avoidance during terrain flight operations. Several major aerospace companies have become involved in the effort to design an obstacle avoidance system (OASYS) that would effectively detect obstacles and provide the pilot with warning in time to effect an avoidance maneuver.

In 1988 the McDonnell Douglas Helicopter Company (MDHC) conducted a study to evaluate four OASYS detection sensor configurations and two detection ranges to determine whether any combination of sensor and range would be effective in enhancing a pilot's ability to avoid obstacles [Ref. 1]. The operational scenario used to evaluate the system was a contour flight mission that was flown at 80 knots in the MDHC Advanced Apache dome simulator. The mission was flown over a data base that modeled a canyon at standard sea level with one kilometer of Forward Looking Infra-Red (FLIR) visibility. The four OASYS detection sensor configurations were defined by the US Army CECOM Center for Night Vision and Electro-Optics (C2NVEO). They varied in four parameters: field of view (FOV), frame time (FT), slewing method and stabilization method. These four configurations are outlined in Table 1. Two detection ranges were tested with each sensor model configuration; these ranges were 200 and 400 meters.

TABLE 1. MDHC OASYS DETECTION SENSOR CONFIGURATIONS

MODEL	FOV	FRAME TIME	SLEWING	STABILIZATION
1	6X8	.2 sec	velocity tracked	pitch
2	20x30	.5 sec	velocity tracked	pitch
3	30x40	.033 sec	head tracked	PNVS
4	30x90	1.5 sec	fixed forward	pitch/roll

A standardized obstacle warning symbol (a triangular cone) was superimposed over the obstacles in the FLIR image during flight to alert the pilot of impending obstacle contact. This very simple symbology was used by each of the eight test pilots to alter their flight paths to avoid obstacle contact.

The conclusions of this study were: although while the pilots generally felt that the OASYS was effective, Model 1 was not a satisfactory configuration and the 200 meter detection range was inadequate. Also, Model 4 with the 400 meter detection range received the highest average rating. MDHC concluded that additional study would be required to investigate further the individual parameters such as FOV and FT, and to study pilot information requirements and symbology issues.

A second study was conducted by MDHC on OASYS in 1990 and 1991 [Ref. 2]. The purpose of this study (termed OASYS II) was to examine an intermediate detection range of 300 meters and to investigate alternative symbologies. The study incorporated the same 20 x 30 degree FOV, velocity-tracked sensor used in the previous study (Model 2) set to a detection range of 300 meters. The operational scenario, environmental conditions, and aircraft performance model were maintained as they existed in the initial study.

The results of OASYS II supported the fact that the OASYS was effective in helping pilots avoid obstacles and that the 300 meter detection range was sufficient, but not as effective as the 400 meter sensor had been. Also, the alternative symbology was determined to be useful for the tested conditions. MDHC concluded again that more research would be necessary with specific emphasis on OASYS performance for terrain detection and avoidance and on symbology concepts when multiple obstacles exist within a FOV and range.

In addition to these results, researchers in OASYS II discovered that FOV problems existed as a function of turn rate and turn radius. While this was not a major area of study for OASYS II, this observation is significant because it represents the first indications of degradation in OASYS effectiveness due to maneuvering flight.

In 1991, C2NVEO contracted Northrop Aerospace to design a system that would alert the pilot to impending obstacle contact. The contract required the OASYS to be compatible with the NVG heads up display (HUD) that is being incorporated into the Army's aircraft in 1992, and to provide adequate warning to the pilot of impending obstacle contact at speeds of up to 100 knots, in maneuvering flight of up to two g's, and at flight altitudes of down to zero feet.

To this end, Northrop has developed a prototype OASYS along with the algorithms which define the system's operational parameters. These algorithms will be flight tested in simulation in 1992, at the Crew Station Research and Development Facility (CSRDF) of the Army Aeroflight dynamics Directorate at Ames Research Center. Following simulation testing, the system will be flight tested by Northrop in 1993.

Northrop's prototype OASYS features a LADAR (which stands for LAser raDAR) scanner which will be mounted to the nose of the aircraft and detect obstacles as they enter its field of view. Obstacle information is then processed and relayed to the pilot through symbology that appears in the NVG HUD. Symbology issues will be addressed in a series of tests conducted during the 1992 CSRDF simulation.

The prototype OASYS that is currently being developed by Northrop and that will be studied in simulation at the CSRDF and flight tested by

Northrop, does not have pitch axis freedom. The system will be mounted to the nose of the aircraft at a fixed angle and will maintain the same pitch attitude as the aircraft to which it is mounted throughout the flight.

Although the addition of pitch axis stabilization or control to this prototype is being considered by Northrop, this has not been accomplished to date. Furthermore, adequate research in the area of pitch axis characteristics for the OASYS has not been conducted. Therefore, it is a purpose of this study to investigate the pitch axis characteristics of the OASYS prototype by determining system effectiveness in maneuvering flight in which significant pitch attitudes are achieved. The results of this study should aid in understanding the present system's pitch axis behavior.

It is important to note that all references to OASYS in this study refer to the prototype Northrop OASYS, which does not incorporate pitch axis freedom. Also, while data in this study is being obtained from simulator flights at the CSRDF, this study is being conducted independently of the CSRDF investigations involving OASYS.

B. OASYS DESCRIPTION AND OPERATION

In designing OASYS under contract to C2NVEO, Northrop faced four major challenges. First, a sensor had to be developed that is eye safe at the aperture, but that could detect obstacles at long ranges. Second, high speed processors had to be designed to ensure that updated obstacle avoidance information would be available continuously. Next, an effective man/machine interface had to be developed to communicate detected obstacles (or the lack thereof) to the pilot. Finally, cost, weight, volume specifications had to be met. What follows is a description of the Northrop OASYS prototype and an

explanation of its operation. All figures and specifications in this section were taken from Reference 3.

OASYS operation is depicted in the block diagram of Figure 1.

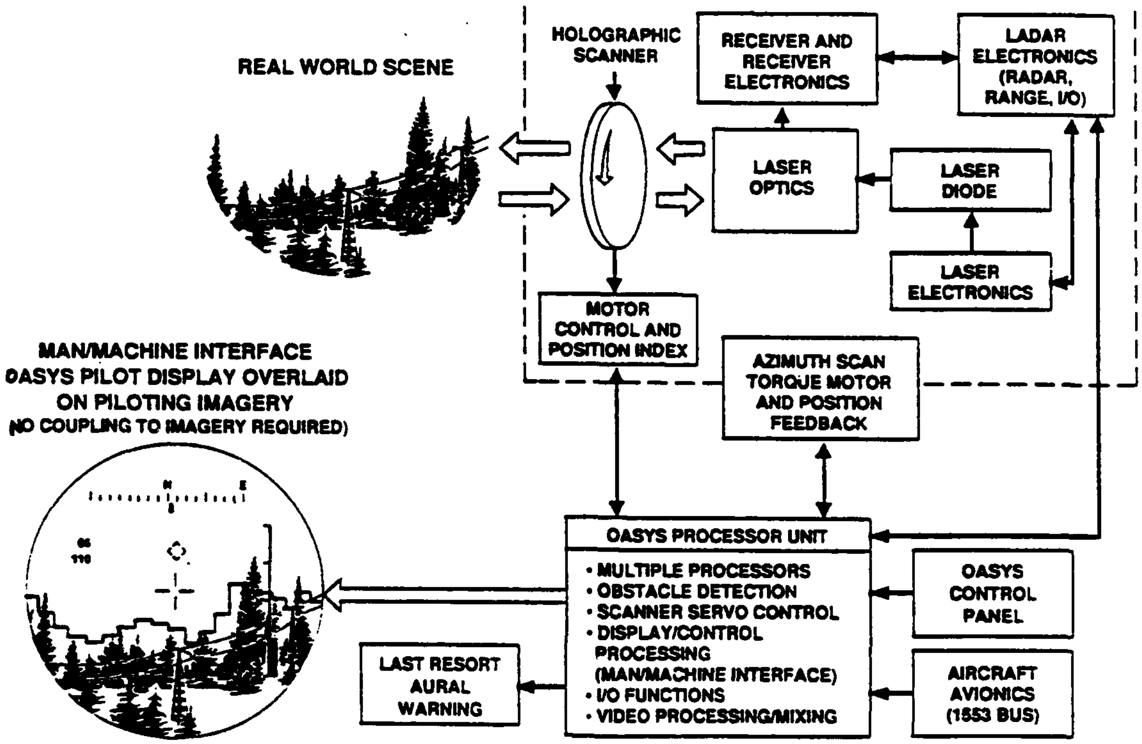


Figure 1. OASYS Block Diagram

The system is centered on emerging technology and features a LADAR which operates exactly as a conventional radar except that it operates in a frequency range that provides greater resolution and thus allows better detection of thin targets (e.g. wires). A laser diode produces pulses of electromagnetic energy with a wavelength of 860 nm. This wavelength energy is capable of producing significant reflected energy from contact with all obstacles that could be encountered in a tactical environment, including small diameter wires, even when they are wet. Conventional radar systems are

incapable of producing sufficient reflected energy under these conditions. The intensity of the laser energy at the aperture for the system is below the threshold intensity which could cause eye damage and therefore, the system is eyesafe.

As the laser fires, the beam passes through the heart of the scanner: the holographic optical element or HOE. The HOE is installed on a circular glass substrate that is rotating at a rate of 6600 RPM (the period of one rotation =1/110 sec); it provides a lightweight, dynamically balanced medium by which the laser beam can be directed. As the beam passes through the rotating HOE it is deflected 12.5 degrees; the rotation of this reflected beam provides a circular scan pattern along the flight path (see Figure 2).

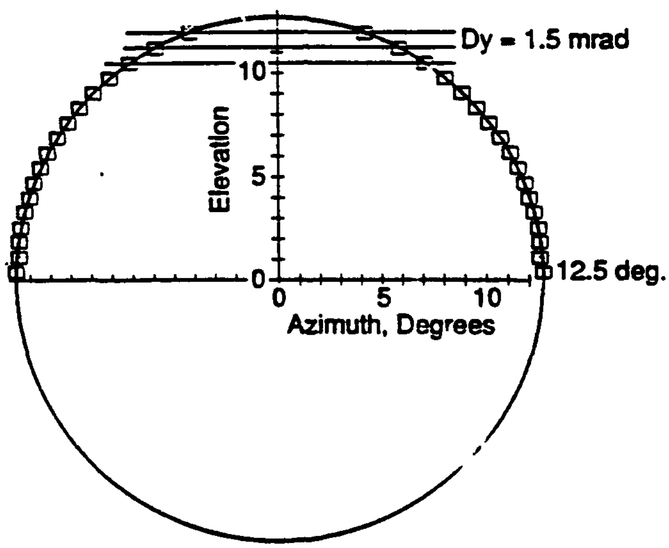


Figure 2. OASYS Individual Circular Scan Pattern

It is important to note in Figure 2 that the 576 laser pulses for each revolution of the HOE are equally spaced around the circular scan in *elevation*; the nominal spacing is 1.5 milliradians of sensor line-of-sight

elevation. Equal spacing is accomplished by varying the timing of the pulses around the scan circle, with the highest rate of pulsing at the equator and the lowest rate of pulsing at the poles. This method of spacing the pulses results in a situation in which the density of the pulses everywhere in the scan pattern is constant. Thus, resolution of objects is equally good throughout the scan pattern.

This circular scan pattern of constant diameter of 25 degrees is superimposed on an azimuthal slewing of the OASYS turret +/- 12.5 degrees about the aircraft centerline, thereby providing a field of regard of 25 x 50 degrees in azimuth along the aircraft's longitudinal axis (Figure 3). In the prototype OASYS, the holographic scanner is mounted to the nose of the helicopter at some fixed pitch angle; for the purpose of this research, the scanner is assumed to be boresighted along the armament datum line of the aircraft.

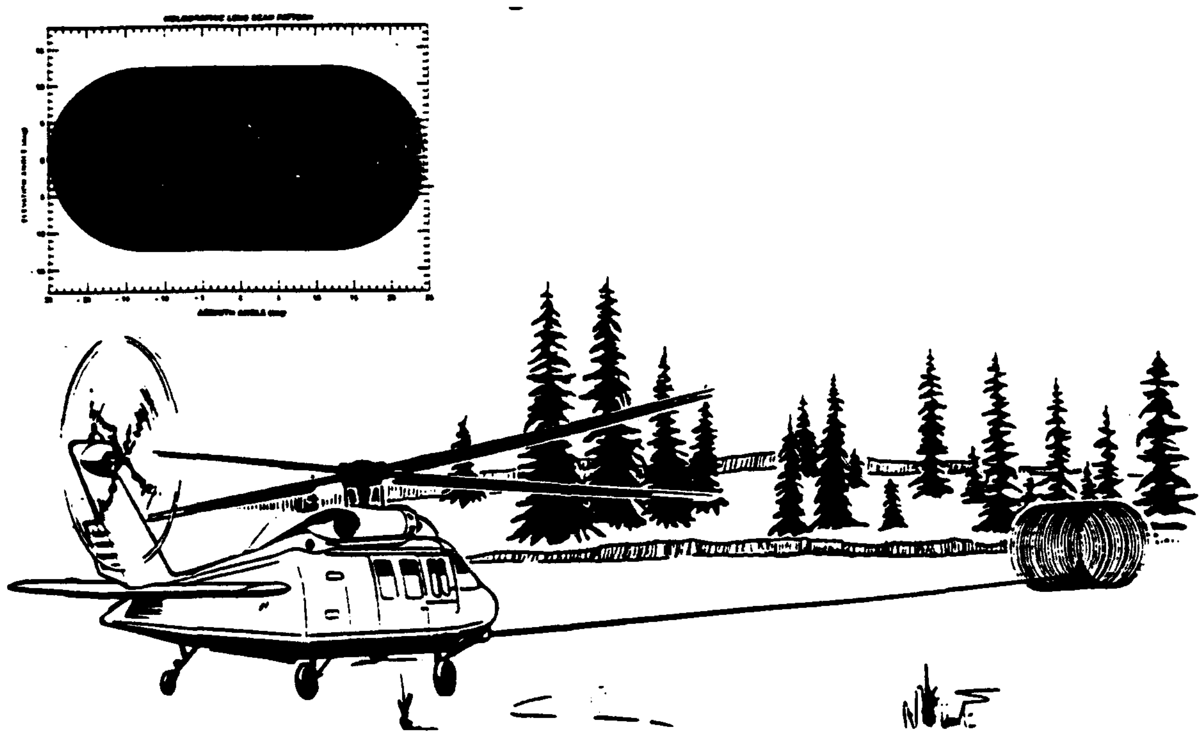


Figure 3. OASYS Scan Pattern

The nominal azimuth scan period is .75 seconds (this time represents the time required for the scanner to scan from the centerline position to its full left or right limit and back to the centerline). This results in a scan rate of approximately 36 degrees per second.

The scan rate is compensated during turning flight in order to maintain constant pulse density during turns. The control laws for the scanner motor result in a slowing of the azimuthal scan rate in the direction of the turn and an acceleration of the scan rate away from the turn. Figure 4 depicts the scan geometry for the OASYS in a 25 degree/second right turn at 100 knots. At least part of the scan pattern is maintained on the horizon throughout the maneuver.

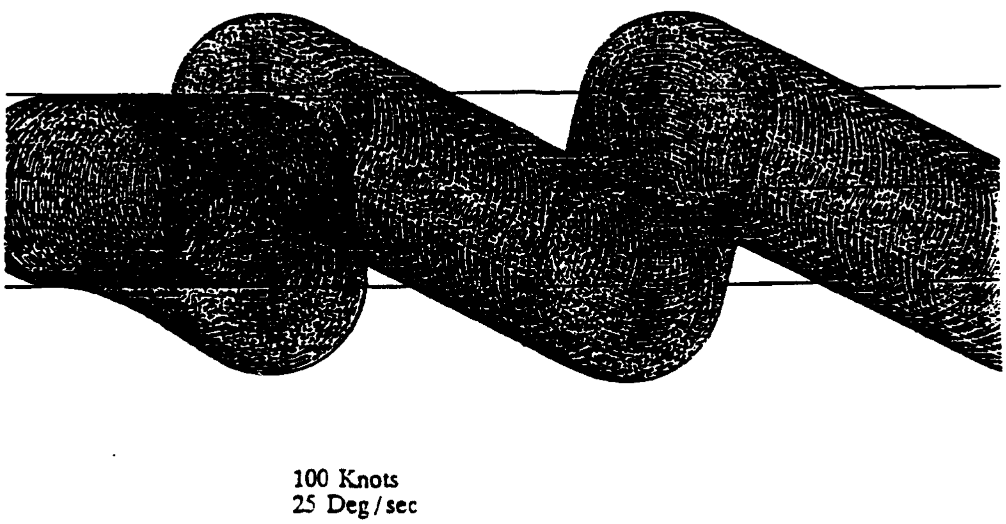


Figure 4. OASYS Scan Geometry in a 25 degree/sec Right Turn

The sensor's avalanche diode receiver is capable of detecting LADAR scatterings off virtually any object within the field of regard of the scanner out to 600 meters. Obstacles which provide returns from ranges in excess of this range are not recorded or stored by the system. The maximum distance for detection for each individual obstacle is a function of size, orientation to the flight path and atmospheric conditions. The specifications for detection of each type of obstacle are given in Table 2. A minimum range of 50 meters is also required for object detection.

TABLE 2. OASYS SENSOR DETECTION SPECIFICATIONS

TYPE OF OBSTACLE	RANGE (meters)
3/8 inch wire	300
1 inch wire	400
trees	600
poles/towers	600

The scattered laser pulses are captured by the sensor and directed through the HOE, which again redirects the signal 12.5 degrees. The signal then passes through several processors which perform a number of functions. The first processor sorts the signals into two types of obstacles (either a "blob" or a "wire") and locates these obstacles with respect to the aircraft. Other processors transform those locations into "window of safety" (WOS) coordinates and transmit usable information in the form of a WOS display to the pilot.

The first processor receives the signal from the receiver as an individual pixel whose corresponding laser pulse produced a scattering off an object within the scanner's field of view. It is grouped with other pixels whose

signals also produced scattering, and with pixels which did not receive a scattering of the laser pulse. These pixels are then processed and correlated along the circular scan of the scanner. Based on the orientation of these correlated pixels, the object that produced the scattering is labeled a "blob" (which could be a tree, pole, the ground, etc.) or a "wire." The range, azimuth and height of the objects' centroids are stored with respect to the aircraft at the time of the laser pulse. These object locations are then used to produce a WOS (which will be discussed shortly) or other symbology to alert the pilot to the presence of obstacles.

The second processor, running asynchronously from the first, applies a WOS display calculation to all stored objects. At a rate of 15 times each second this processor scans all of the objects which have been detected within the previous 30 seconds and calculates a *compensated elevation* (which will be discussed shortly) for each object therein. It then produces or updates a WOS display based on azimuth bands.

The WOS display depicts a region in space oriented on the aircraft's flight path vector. It provides the pilot with a clear picture of what objects exist along the flight path vector and where they are in relation to the aircraft's position if flight is continued at the current state. Within each azimuth band, the highest compensated elevation is selected, and that elevation presented to the pilot on the HUD symbology. Objects that the aircraft will clear by a safe altitude at its present state (airspeed, rate of climb, etc.) are depicted on the WOS as equal in height to the aircraft marker (ACM) (Figure 5). Taller objects will rise above the aircraft marker (Figure 6) and shorter objects will fall below the marker (Figure 7). All WOS displays presented in

this study were produced using the BES computer simulation programs and are reproduced herein with the permission of that company.

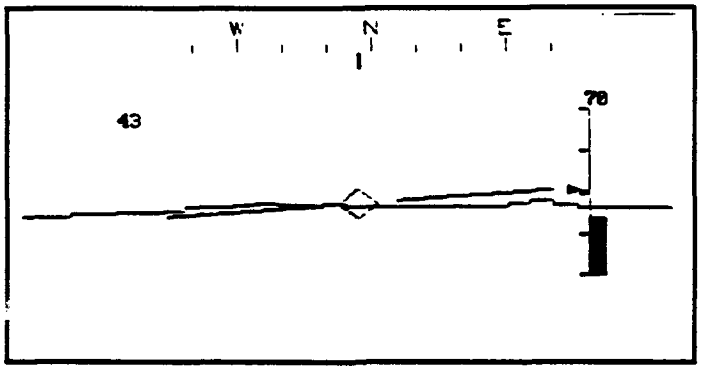


Figure 5. WOS Display with ACM Equal to WOS Height

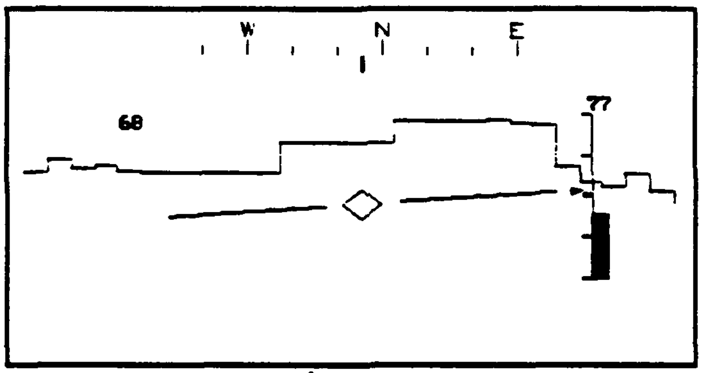


Figure 6. WOS Display with ACM Below WOS Height

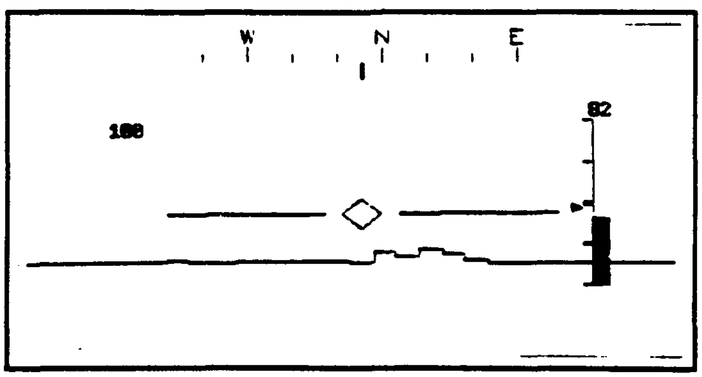


Figure 7. WOS Display with ACM Above WOS Height

The compensated elevation calculation is critical to the system in that it allows pilots to determine how aggressively they will fly the system. The algorithm is a function of airspeed, sensor range, rate of climb, and three pilot-selected parameters: *safe altitude* (the altitude at which the pilot wishes to cross all obstacles), *delay time* (the time that elapses from the pilot's seeing the symbology to the time he reacts to it), and *vertical acceleration* (the amount of acceleration in g's that a pilot is willing to have to make to avoid an obstacle). These three parameters are a function of pilot experience, threat, mission, etc., and may be selected from the cockpit. Thus, if a pilot desires to remain low until he is very close to an obstacle, with the parameters set accordingly, the WOS will provide him with indications that contact is not imminent until the obstacle is very close. On the other hand if the pilot wishes to fly a less aggressive flight profile, the system will provide WOS indications accordingly.

The window of safety is the symbology that Northrop is proposing to use with OASYS. However, as mentioned, alternate symbologies are presently under investigation at the CSRDF. While the window of safety will be used to describe the results of the computer simulation in this study, the symbology chosen is immaterial. *Only issues regarding the system's effectiveness in detecting and locating obstacles in the flight path are relevant, and these are independent of the symbology selected.*

C. NATURE OF THE PROBLEM

In tactical situations, helicopters can generate extremely high rates of turn, pitch rates and pitch angles. This raises the real possibility in tactical flight of the pilot's "outflying" the capability of the prototype OASYS.

In the MDHC tests, the aircraft simulators were flown tactically, but pitch attitudes did not present a problem for the sensor because the sensor was horizontal velocity-tracked. Similarly, during the MDHC testing, the pitch degree of freedom was not considered. The sensor was stabilized on the horizon and never deviated during maneuvers. Furthermore, the operational scenario in which these tests occurred never required the pilot to perform aggressive pitch change maneuvers such as accelerations or decelerations.

The Northrop prototype OASYS has been computer modeled and tested throughout a range of turning maneuvers by BES, a subcontractor to Northrop. Results indicate that this configuration will provide effective obstacle avoidance information to the pilot in most turning maneuvers. However, at the design specification's maximum values for airspeed and g-loading (100 knots and two g), OASYS provides only 1.2 seconds of look-ahead [Ref. 4]. Also, turn rates in excess of 25 degrees per second were not considered in this testing.

Furthermore, maneuvers which generate large pitch angles were not tested. In fact, during the initial BES computer simulations, pitch attitude was not considered a degree of freedom; the sensor's pitch attitude was stabilized on the horizon. Because the Northrop OASYS prototype does not incorporate a stabilization or control system to maintain the sensor's position in pitch, it is imperative that aggressive pitch-causing maneuvers be examined prior to flight to determine the regions for which the OASYS will provide adequate obstacle avoidance information to the pilot throughout these maneuvers.

It is the primary purpose of this investigation to determine through the use of computer simulation the Northrop prototype OASYS' effectiveness in

providing adequate and accurate obstacle avoidance information during high rate of turn and acceleration (pitching) maneuvers. If specific maneuvers are found that render the OASYS ineffective, then a general envelope of flight parameters will be developed to assist researchers and pilots in improving the capabilities of the system.

D. RESEARCH PLAYER ORGANIZATION

At this point it is important to outline the relationships of the organizations which play a key role in OASYS research and development. The figure below depicts the organization of these players.

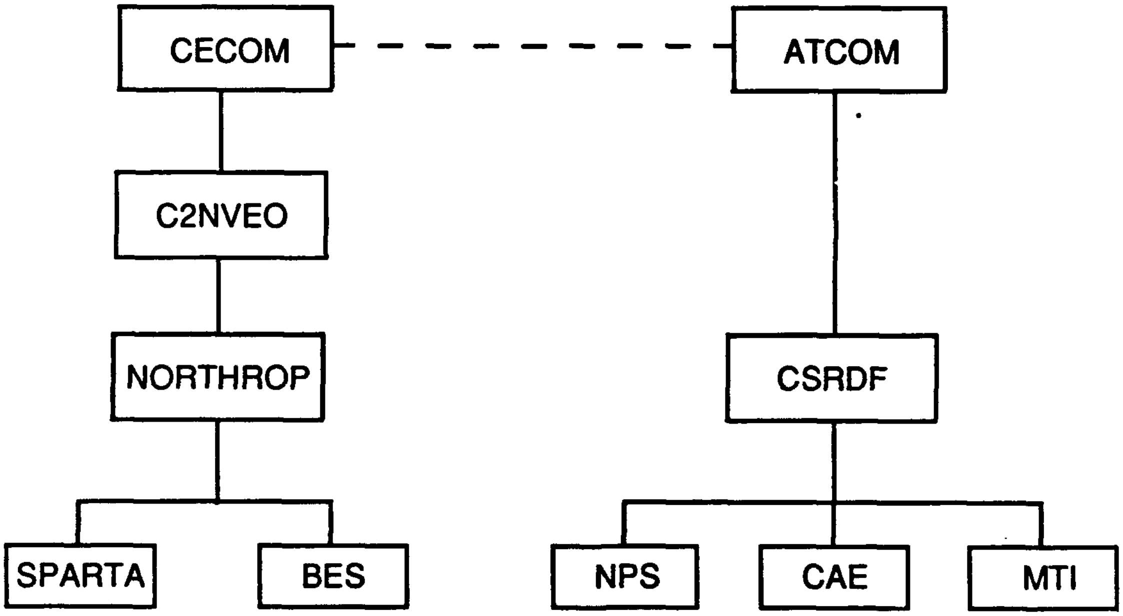


Figure 8. Organization of Key Players

Northrop was placed under contract by ATCOM in January 1991 to design and develop a lightweight prototype demonstrator for obstacle avoidance; the project manager for Northrop was Mr. Rolf Krumes. Mr. Krumes

then placed several subcontractors, including BES, a small engineering company owned by Mr. Carl Bose, on contract to help with this task.

During the development of the system, ATCOM determined that research staff at the CSRDF would become involved to assist Northrop by providing a simulator in which the OASYS could be tested prior to full flight test; CSRDF staff was also tasked to investigate symbology and man-machine interface issues. Monterey Technologies, Inc. (MTI) investigated the symbology issues of OASYS. CAE, a Canadian-based software engineering firm, handled software design and integration, in addition to operation of the CSRDF flight simulator.

This study was begun in conjunction with CSRDF personnel after a meeting involving symbology issues, during which concerns about the effectiveness of OASYS during maneuvering flight surfaced. After researching the subject, it was determined that a computer simulation should be conducted in conjunction with BES to study the effects of maneuvering flight on the OASYS. Thus, although this research was conducted independently of the CSRDF simulations, it provided a link between the CSRDF, Northrop (through BES), and the Naval Postgraduate School, a situation from which all benefited.

II. EXPERIMENTAL APPARATUS

A. CSRDF ROTORCRAFT SIMULATOR

The maneuvers for which OASYS was evaluated through computer simulation were flown at the Crew Station Research and Development Facility (CSRDF) at Ames Research Center. The CSRDF operates an advanced rotorcraft simulator which incorporates the latest improvements in simulation technologies. Its "virtual world" representation very closely replicates the physical environment of the real world; in fact, it was used to train pilots that would eventually conduct the Army's LHX flyoff. What follows is a description of this simulator and the equipment used to generate the aircraft flight parameters which were recorded during the maneuvers flown.

The crew station simulator is comprised of a two-seat tandem helicopter cockpit, a wide field of view helmet mounted display system (WFOVHMD), and the Experimenter/Operator console (EOC), all integrated with and driven by a VAX 8650 computer system. A schematic of the system is given in Figure 9 [Ref. 5].

The tandem cockpit incorporates the latest technology in aircraft controls, displays, and instrumentation. The simulator may be flown from either seat by using a single four-axis hand controller; alternatively, the pilot may select any combination of two control sticks and conventional tail rotor pedals to control the simulator in the four axes. The cockpit instrumentation is digital and incorporates touch screen CRT displays. The Tactical Situation

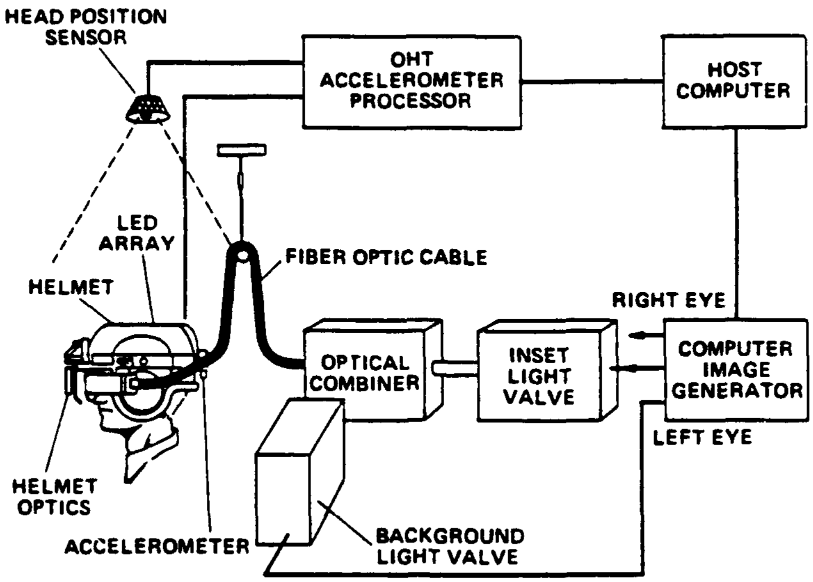


Figure 9. Crew Station WFOVHMD System

Display (TSD) is a touch sensitive CRT which is located in the front of the cockpit and provides the pilot with tactical situation, navigation information, and threat/friendly situation overlaid. Also within easy reach of the pilot are several panels with switches for system control, and for tactical data entry. Finally, in order to provide a highly realistic flight environment, a six channel sound system surrounds the crew station. This system provides directional sound cues for rotor and transmission noises as well as other noises that might occur in a tactical scenario. A schematic of the cockpit arrangement and an overhead view of the front seat are given in Figures 10 and 11[Ref. 6].

The primary flight instrument for the pilot is the WFOVHMD system which presents an instantaneous 120 degree horizontal and 67 degree vertical field of view (FOV) of the virtual world with superimposed flight symbology

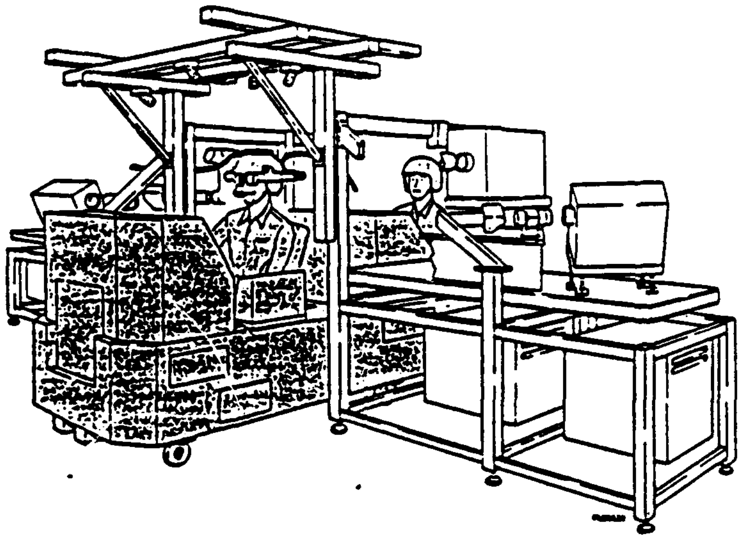


Figure 10. Crew Station Structure

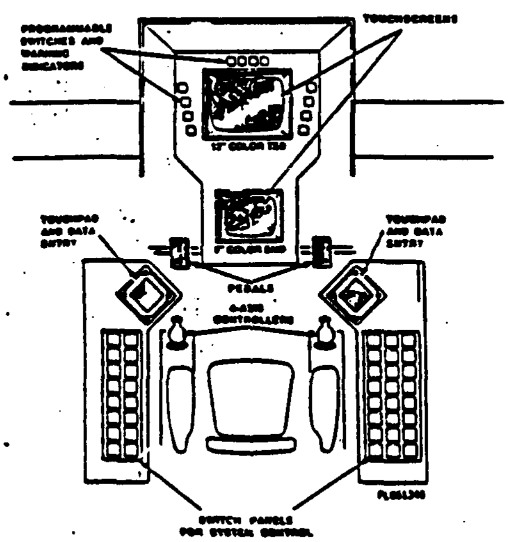


Figure 11. Overhead View of Front Crew Station

and tactical data. The system consists of two sets of optics fitted into a lightweight helmet (Figure 12) which is worn by the pilot. Visual imagery is computer generated by a Compuscene IV computer generated imagery (CGI) system and transmitted to the helmet optics by two fiber optic bundles through four light valve projectors. Using a 60 x 60 nautical mile data base constructed for the OASYS simulation, the Compuscene IV system provides FLIR, day-color, or NVG imagery of the virtual world to the pilot with a high degree of resolution. The system provides imagery to each eye through the optical combiner; the superposition of these images produces the FOV depicted in Figure 13. The high resolution inset depicted in the figure is a region directly in the middle of the pilot's FOV for which the resolution is optimized [Ref. 5].

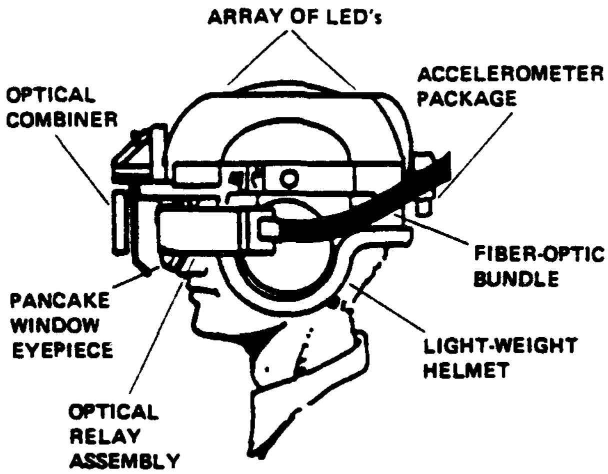


Figure 12. Crew Station WFOVHMD Helmet

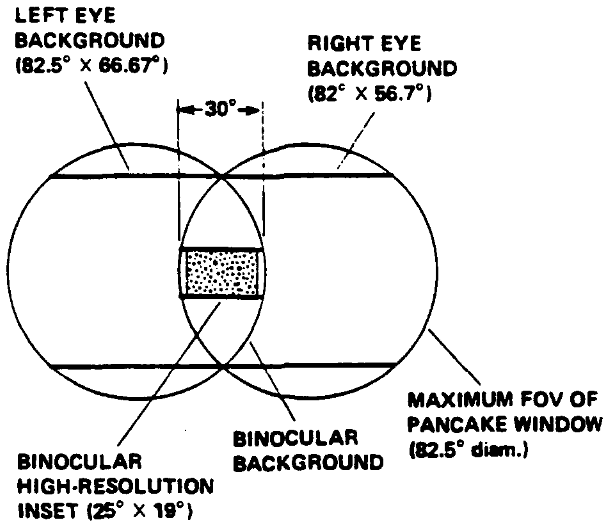


Figure 13. WFOVHMD Field of View

An IR head tracker, using an LED array mounted to the helmet, monitors the pilot's head position and head movements to ensure that the image generator produces a visual representation of where the pilot is looking. Accelerometers are affixed to the pilot's helmet to provide lead predictions to compensate for delays in producing and transmitting the visual imagery. Thus, this system produces a very stable, real-time image with a field of regard (FOR) that is essentially unlimited.

The Experimenter/Operator console (Figure 14) is the station from which the experiment or flight may be monitored and recorded [Ref. 6]. From this console, researchers may view the flight with ultra high resolution monitors and displays which repeat the outputs of the image generating system. Radio communications enable researchers to advise pilots during the flight and to monitor their tactical radio transmissions. Also from the EOC, researchers

can manipulate the data base, reposition the aircraft, or restart the aircraft in the case of a crash.

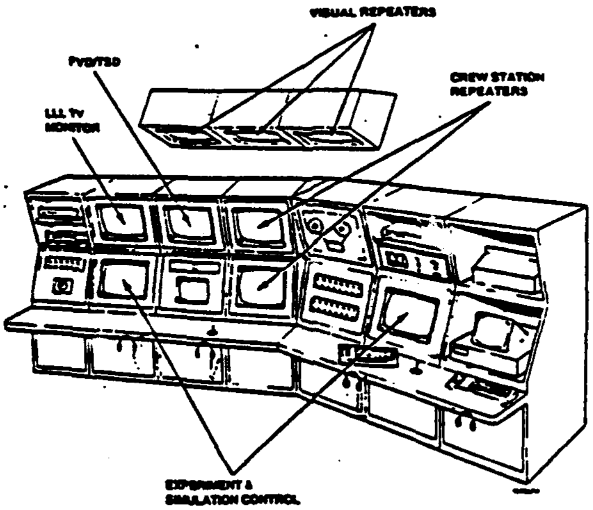


Figure 14. Experimenter/Operator Console

The whole system is coordinated and powered by a VAX 8650 computer system, which models the flight control simulation with a blade element model. This model, which partitions each blade into segments and computes lift and drag for each segment, provides excellent simulation for all modes of flight, especially during the transition from NOE to higher airspeeds. The system's software is modular and adaptable, and thus, the model may be changed simply by exchanging software. In its present configuration, the simulation software most closely models the flight dynamics and performance of a UH-60 helicopter.

The VAX 8650 system provides researchers with the ability to monitor and output numerous flight parameters throughout the flight. These flight

parameters may be recorded as time history plots using a Printronix Model P printer.

B. BES OASYS FLIGHT SIMULATION PROGRAM

The BES OASYS flight simulation program is essentially five separate executable programs that may be run on IBM compatible computers. Running at 400-1000 times slower than real time due to its complexity, it models the operation of the actual OASYS hardware (25 degree FOV, 860 nanometer wavelength, beam divergence equal to 1.5 millirads, etc.) and exactly mechanizes the processes which the OASYS data processors use to process the radar return data.

The first of the five programs is the *radar simulator program*, which models the aircraft motion, the scanner dynamics, the radar beam, and the radar receiver. This program contains the data base of object locations and descriptions and allows simulated flights of up to 29.82 seconds to be flown over it. The program accepts as input a data file that was created for each maneuver describing the flight dynamics of the aircraft during the maneuver. For this study, these data files were created from data generated during flights in the CSRDF simulator. This program then compares the position of the aircraft relative to the known data base objects and determines which of almost two million radar pulses during the flight are received by the receiver. The outputs of this program are two data files, one containing a simulated radar return output, and one containing aircraft position, velocity, and attitude data in three dimensions for each rotation of the scan circle.

These outputs are accepted as inputs to a *filter simulator program* which models the signal data processing algorithms of OASYS. It processes the raw

radar data and generates an object location for blocks of 72 possible radar returns. It classifies objects in each block as a "blob" or a "wire" and outputs a data file which contains the descriptions of these objects found by this signal data processing.

An example of the filter simulator program output is given in Figure 15. This figure represents the processed radar return data for an entire frame of 1.5 seconds (or two full translations of the scanner). Dark areas on the radar plots represent positions where pixels received radar returns during the scan; black areas were classified as "wires" and gray areas as "blobs."

The *left* half of the figure represents the returns detected by the scan of the *right* half of the scan circle; the *right* half of the figure represents those detected by the *left* half of the scan circle. Each vertical line of pixels in each plot represents the radar returns detected by the corresponding side of *one* circular scan which have been "straightened out" during processing. The horizontal axis on each half plot is a time axis and represents 1.5 seconds of the flight. The time corresponding to the sensor's scanning from left to right is distinguished by a solid bar running across the top of the figure; the time corresponding to the scanner's right to left scan does not have a corresponding bar at the top of the figure. When these two half plots are superimposed, a radar return summary of one entire frame results.

The given points on the figure correspond to the points depicted on the auxiliary figure to aid in understanding how the processor superimposes the two half plots to obtain information that will be used to construct the WOS display. Also, the trees in the radar display are numbered and correspond to the numbered trees in the auxiliary figure. Note the symmetry that is

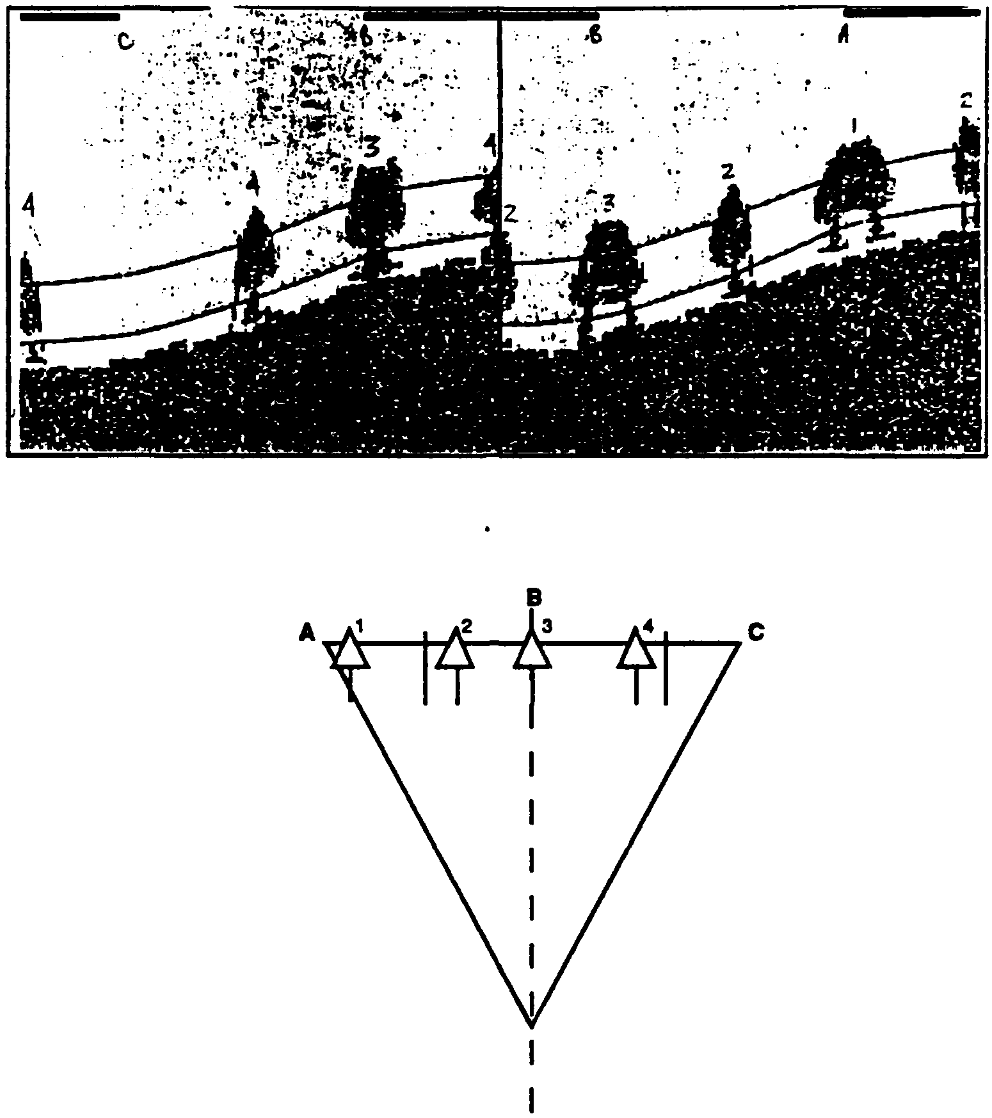


Figure 15. Processed Radar Data During Pitch Down Maneuver

exhibited in these plots around the point at which the sensor's scan changes directions. Also note that the tree at point B was detected by both the right and left halves of the scan circle, and thus appears on both half plots. Its radar plot is slightly different in each half because the time at which the tree was scanned by each half of the scan circle was different, and thus the

aircraft position had changed. Also of importance to note is the tendency of each half plot to rise in altitude as time progresses on the horizontal axis. This is due to the downward pitching of the aircraft which starts in this frame; the objects therefore appear higher in the scanner FOV as the frame progresses in time.

The *display simulator* mechanizes the display algorithms of OASYS, generates WOS symbology, and superimposes it on the pilot's HUD symbology. The inputs for this program are the output from the filter simulator program, and the aircraft dynamics output from the radar simulator. For convenience, this program, unlike the actual OASYS, synchronizes the signal data processing with the WOS display generation and thus, produces fewer WOS displays per 29.82 second flight than would the actual OASYS (400 vs. 447). However, this is not a problem since the purpose of this study is to evaluate OASYS accuracy, which can be done just as effectively with only 400 WOS displays.

The next program provides the researcher with a means of viewing and studying each of the 400 WOS displays. This program plays back the 400 WOS displays in either real time or at any slower speed which the viewer chooses. The program may also be stopped at any time and the displays stepped through one at a time to allow the researcher to evaluate the changes to the WOS display as the flight progresses.

The fifth and final program draws the graphs of the flight parameter data that was recorded in the data file which serves as the input to the radar simulator program.

A flight using this simulator consists of 20 frames-each frame is 164/110 seconds in length (or about 1.5 seconds). Each 1.5 second frame is further

divided into 20 steps, each of which corresponds to one WOS display. Thus, each 29.82 second flight is comprised of 20 frames and 400 steps.

Associated with the program is its data base which consists of trees, poles, wires, and other objects typically appearing on a tactical landscape. The dimensions of the objects therein were derived from photographs of the actual objects which were then scanned into a file with a computer scanner. An example of a standard data base is depicted in Figure 16; it shows the locations of the objects therein. A description of these objects follows in Table 3. This data base is contained in the radar simulator program and may easily be manipulated to provide researchers with any obstacle field required for their research.

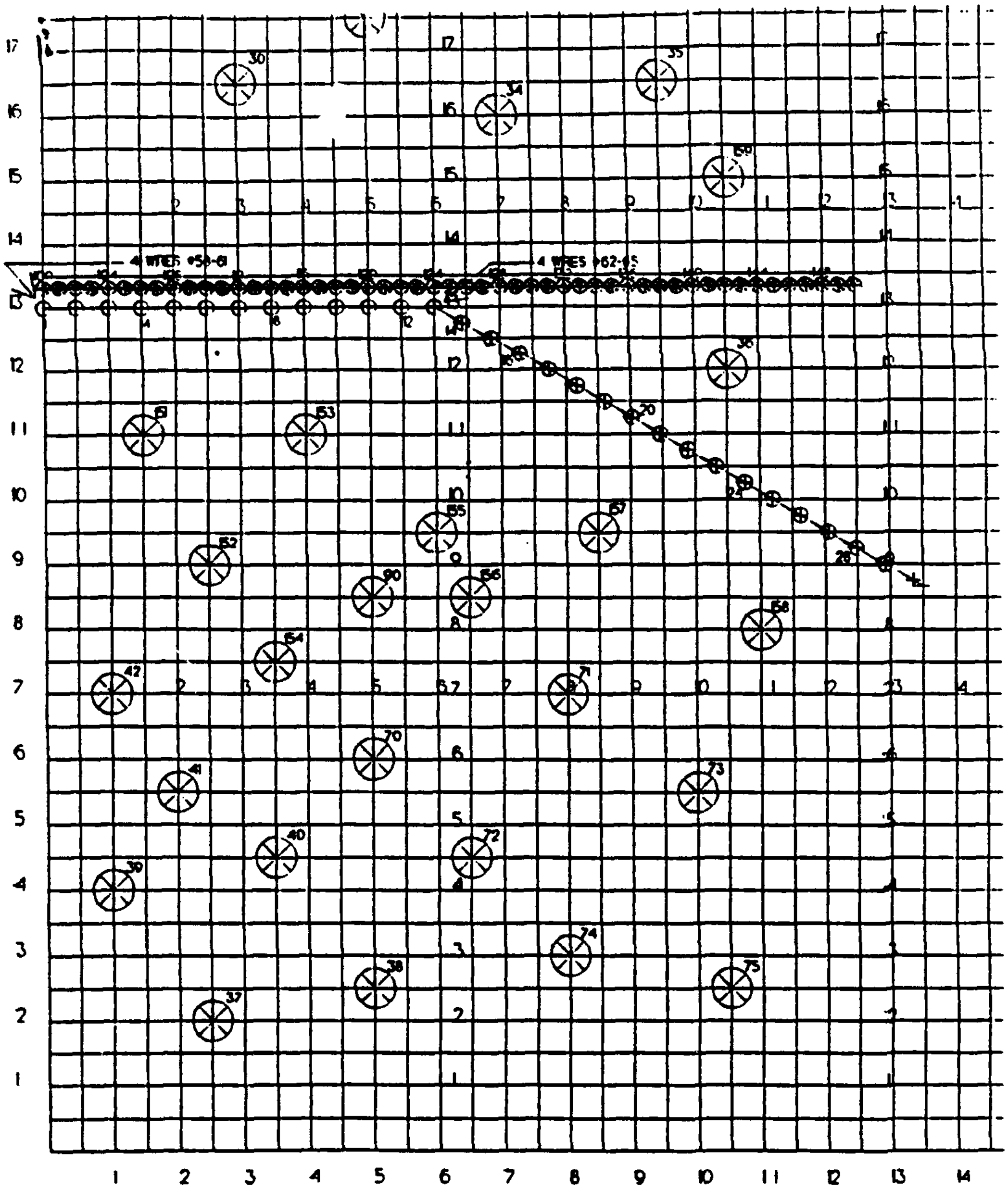


Figure 16. Standard Object Data Base

TABLE 3. DATA BASE OBJECT DESCRIPTION

Objects 1–29	Power poles, 20 meters in height
Objects 58–60 and 62–64	Sets of three wires 19 meters above ground. Located on above poles.
Objects 61 and 65	Wires 7 meters above ground. Located on above poles.
Objects 30–36	Fruit trees with no leaves, approximately 10 meters high
Objects 37–42	Palm trees, approximately 34 meters high
Objects 70–75	Ficus trees, approximately 16 meters high
Object 90	Dead tree, approximately 23 meters high
Objects 100–159	Pine trees, approximately 27 meters high

III. PROCEDURE AND RESULTS

The procedure followed in this study was divided into three distinct phases, with the procedure for subsequent phases dependent on the results of the previous phases. For clarity, the results of each phase will be included directly after the procedure for that phase, and a schematic of the overall sequence followed in this study is given in Figure 17.

Phase I consisted of an initial investigation of several maneuvers flown at the CSRDF, programmed into the BES OASYS flight simulation program, and analyzed on a specific obstacle data base to determine whether or not the OASYS provided effective obstacle avoidance information throughout the maneuver. Analysis of the results of this simulation provided direction and insight necessary to complete Phase II of the study, which consisted of deriving an analytical model of one of the specific maneuvers investigated in Phase I. Phase II included the derivation of an analytical envelope for which the OASYS functioned effectively. Phase III of this study focused on verifying empirically the analytical model generated in Phase II. It consisted of multiple computer simulations of the maneuver studied in Phase II. These simulations were run on a standardized data base designed specifically to allow the results of these simulations to be generalized.

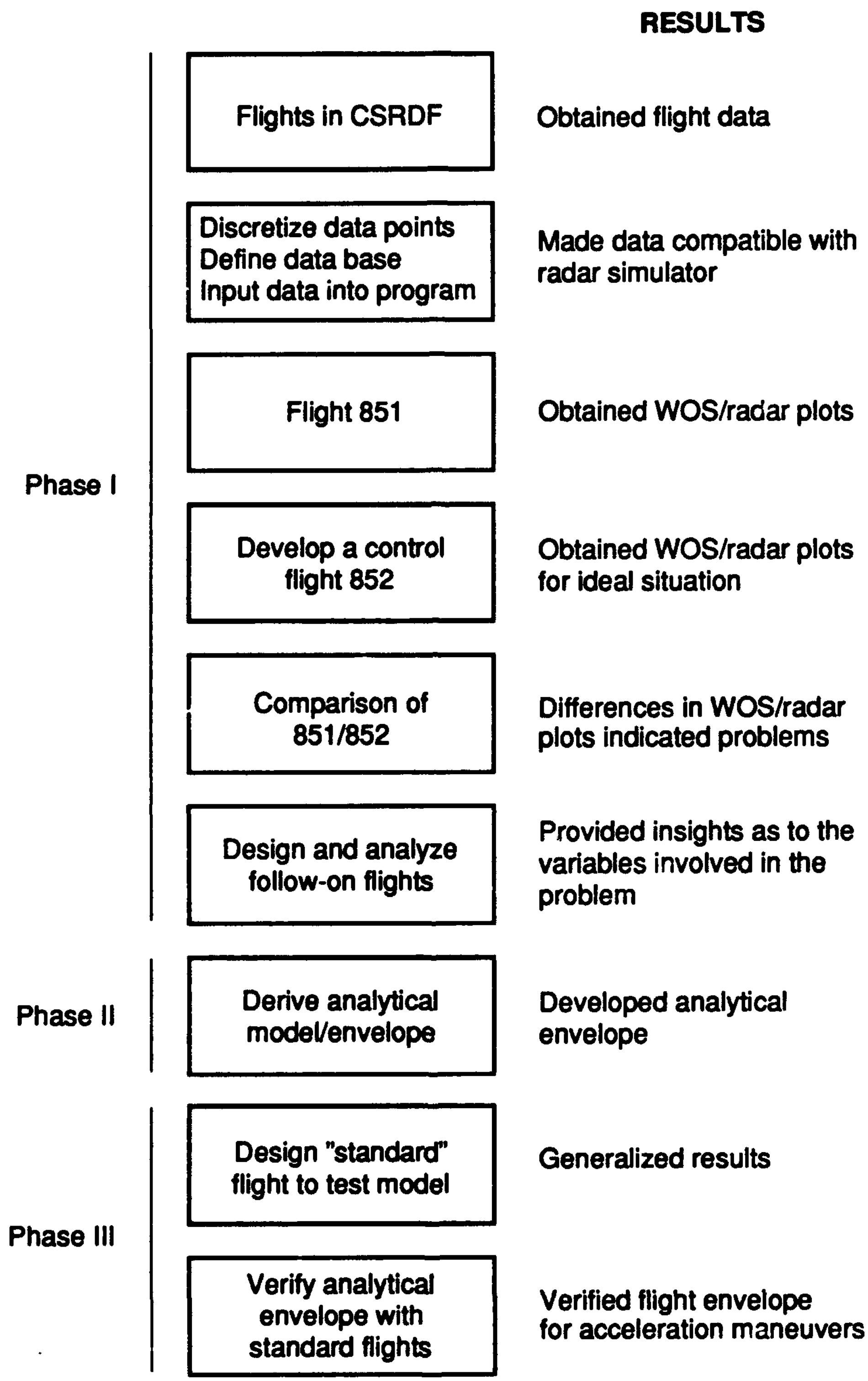


Figure 17. Schematic Procedure Followed During Research

A. PHASE I

The procedure for Phase I consisted of the following steps: selecting the maneuvers to be investigated, flying those maneuvers in the CSRDF and recording the flight parameters as a function of time, discretizing these flight parameters and programming the BES simulation program with this data, choosing the data base over which the maneuvers would be flown, and finally, analyzing the results of the computer simulation flights using both radar return plots and OASYS symbology.

1. Maneuver Selection

Over two dozen 30 second maneuvers were flown in support of this investigation in the CSRDF simulator. These maneuvers included slaloms, high-rate level turns, hovering turns, level accelerations, decelerations, and lateral sidesteps. However, as the study progressed, the focus of this investigation became centered on those maneuvers thought most critical for OASYS, which were rapid hovering turns and pitch inducing maneuvers. Thus, most of the CSRDF maneuvers were not analyzed. Those that were eventually used for analysis during this study are listed in Table 4; an example of their corresponding flight parameter time history plots is given in Appendix A.

TABLE 4. CSRDF MANEUVERS USED FOR ANALYSIS

MANEUVER	DESIRED PARAMETERS
Hovering flight	0 knots
Steady state flight	50, 70 100 knots
Aggressive acceleration	2.8 m/sec^2
Gentle acceleration	1.0 m/sec^2
Hovering turns	50 degrees/sec

The flight parameters which the pilot of the study attempted to attain during each maneuver were derived from several sources. The OASYS specification document provided initial parameter limits. It requires the OASYS to provide obstacle avoidance information at speeds of from zero to 100 knots; thus accelerations considered in this study have an upper velocity limit of 100 knots and a lower limit of zero.

Secondly, ADS-33C [Ref. 7] which outlines the handling qualities requirements for military aircraft, gives specific limits on aircraft flight parameters that should be achieved during flight testing of aircraft. For example, in the degraded visual environment which exists during NOE flight, to properly test an aircraft, the turn rate for a hovering turn must exceed 18 degree/sec, and during accelerations the nose-down pitch attitude must exceed 12 degrees. Applying these specifications to the OASYS is a logical extension of ADS-33C.

Finally, pilot experience and judgment were applied to the maneuvers. Although this source is not quantifiable, it is imperative to apply pilot judgment in assessing maximum turn rates in excess of 18 degrees, for example, that could reasonably be expected to be achieved in the conditions given, and flown in present day aircraft. No maneuvers were included in this analysis that were either uncontrollable or that resulted in a crash of the aircraft.

2. CSRDF Flight Procedures

The simulator flights were conducted from the front seat of the CSRDF advanced concepts rotorcraft flight simulator. The pilot (the author) was an active duty Army Aviator with over 2000 flight hours in helicopters, and over 300 night vision goggle (NVG) flight hours. The flights were

controlled by personnel at the EOC who placed the aircraft on the terrain data base, monitored the flight's progress, and operated the computer printer which recorded the data.

The WFOVHMD system was programmed to display NVG imagery with superimposed HUD symbology to give attitude, radar altitude, airspeed, rate of climb and heading information. The right hand 4-axis controller was selected and used for control of each maneuver; altitude hold was engaged during those maneuvers which did not require an actual ascent or descent. All maneuvers were conducted over flat terrain, with calm winds, and were 30 seconds in duration.

While these maneuvers were being flown, the VAX 8650 was recording the following flight parameters: X and Y position, pressure altitude (Z), pitch, roll, heading, and airspeed. These flight parameters were then produced as time history plots for each maneuver; an example of these original plots is included in Appendix A.

3. Data Reduction

These continuous time history plots were unusable in their raw form. Thus, the data on these plots was discretized and normalized using the following procedure to ensure that the data contained in these plots could not only be used in the BES computer simulation program, but also run from any point on any designed data base.

First, an arbitrary zero was chosen on the y-axis for each major division given on the plots (Appendix A). The value of the y-axis variable at this point was recorded as the *bias value* . Next, a *scale factor* was calculated; this represented the value of the y-axis variable between each major division and was calculated by finding the difference between 10 major divisions and

then dividing this number by 10. Then at intervals of 0.696 seconds (this value represented the time between four of the smallest time divisions on the original plots), the y-axis value of the flight parameter was recorded in units of major divisions and tenths of major divisions.

These values (bias value, scale factor, time interval, and y-axis values) for each flight parameter for each maneuver were then read into a BES utility program which prepared *normalized* X, Y, altitude, vertical velocity, horizontal forward (tangential) velocity, drift velocity, pitch, roll, and heading parameters at a rate of 110 Hz. Thus, a virtually continuous plot of all flight parameters for each maneuver flown in the simulator was reconstructed and stored for use later with the OASYS radar simulation program. These reconstructed flight parameters were normalized so that initial conditions (X,Y, Z, and heading) could be entered into the radar simulation program and the flight be accurately conducted from anywhere on the data base. Also, this normalization allowed the combining of individual maneuvers into composite maneuvers (as will be discussed shortly) without the generation of discontinuities.

4. Flight 851 Design

Based on the available literature and on knowledge of the system, it seemed that the two maneuvers that would be most difficult for the OASYS prototype to deal with would be high rate turns and aggressive pitching maneuvers. Thus, in designing the specific maneuvers to be computer simulation tested, it was decided to combine several of the original maneuvers flown at CSRDF into a composite maneuver that would considerably challenge the OASYS prototype. This maneuver was designated flight 851.

Flight 851 consisted of a rapid 124 degree hovering turn at a rate of 43 degrees/sec, followed immediately by an aggressive, constant, level acceleration at a rate of 2.9 m/sec^2 to 100 knots, followed by straight and level flight at 100 knots until the 30 second limit. An altitude of 20 meters (plus or minus small perturbations) was maintained throughout the maneuver.

The flight parameters for this composite maneuver were programmed into the radar simulation program by accessing the flight parameter data files generated as described earlier. However, the data files were manipulated to generate this composite maneuver from the three maneuver files corresponding to the hovering turn, the level acceleration, and the steady state flight at 100 knots. Thus, the flight parameters file for flight 851 consists of the flight parameters of a 124 degree hovering turn, combined with those of an acceleration, combined with those of steady state flight at 100 knots.

The normalization of the parameters as discussed earlier, allowed them to be pasted together with the generation of no significant discontinuities, with one exception. Because the acceleration maneuver flown at CSRDF did not include a leveling to steady-state flight, the pitch parameter for flight 851 was manipulated so that the pitch attitude transitioned from the attitude held during the acceleration to that maintained in steady flight at 100 knots. The rate for this transition was equal and opposite to that used to pitch down during the acceleration. All other parameters were maintained as flown in the original flight during this process. Thus, a high degree of realism was maintained in the construction of the flight since all minor fluctuations in heading, pitch, roll, etc. wer^ included as they appeared in the CSRDF

simulations. The time history plots for flight 851 are given in Appendix B; a planview of flight 851 is given on its data base in Figure 18.

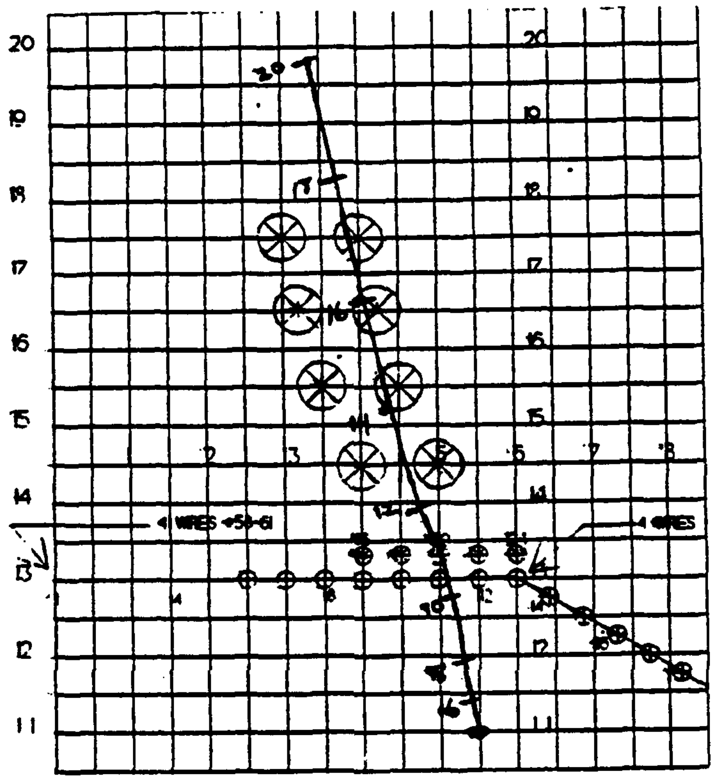


Figure 18. Planview of Flights 851/852

5. Data Base

With a maneuver selected, constructed, and programmed into the simulation program, the data base selection was the final step prior to the running of the program. The choice of the data base was critical since having too many obstacles in the data base could result in confusion during analysis of the maneuver, and not having enough obstacles in the right places could result in inaccurate results.

It was recognized that problems with the OASYS prototype could occur outside the limit of its ability to detect targets at its initial position. Also, during the turn it was imperative to have obstacles within the scanner's range to determine the effects of the turn on the system's effectiveness. Thus, it was determined that a modified BES standard data base would be used and augmented with palm trees as depicted in Figure 18. The aircraft's initial position was selected to place the poles and wires *inside* the OASYS detection range; the palm trees were interspersed along the subsequent flight path at a range initially *outside* the OASYS' sensor detection range.

It should be noted that an infinite number of possibilities exist with respect to design of a data base. The data base designed here was specifically engineered to fully test the OASYS' obstacle detection capabilities under the most demanding circumstances.

6. Simulation Of Flight 851

The computer simulation of flight 851 was conducted on the BES OASYS simulation program over the data base described above. This simulation provided two outputs: the raw radar data plots and the OASYS WOS displays for 400 steps throughout the 30 second flight (see Appendix C). Figure 19 depicts a raw radar plot in frame 10, 15 seconds into the flight (point A in Figure 18). It is obvious from Figure 19 that radar data is being processed, but it appears to be so distorted that it may be providing inaccurate data for processing.

Clearly, the system is detecting the wires, the pine trees and some palm trees. However, because of the distortion of the radar data, it is difficult to identify individual trees, poles, or wires. The OASYS WOS plots alone do not provide exact indications of where the OASYS may not be functioning

properly. It was imperative after this initial flight to design a baseline or control maneuver, against which flight 851 could be checked.

Figure 19. Processed Radar Data From Frame 10 of Flight 851

7. Designing a Control

The problem of designing a control was solved by developing flight 852. Flight 852 consisted of exactly the same flight parameters as flight 851 except that the pitch of the aircraft (and therefore, the OASYS sensor) *was maintained at 0 degrees (on the horizon)* for the duration of the flight. This situation *simulates the condition of pitch stabilization of the OASYS sensor on the horizon.*

Simulation of maneuver 852 should provide radar plots and OASYS WOS displays which model the ideal situation in which little or no distortion of the radar plots due to pitch maneuvering would occur, all obstacles would be detected by the OASYS, and the WOS display would incorporate all obstacles. Therefore, a comparison of flights' 851 and 852 radar and OASYS plots would give an exact indication as to whether or not the OASYS provided accurate information throughout maneuver 851.

8. Comparing Flights 851/852

Each of the 400 steps and corresponding WOS displays for both flights was analyzed to determine whether or not the OASYS provided correct WOS displays throughout flight 851. The key radar and WOS displays for each flight are contained in Appendix C; for clarity, many are also reproduced within the text, and a summary of each flight's WOS displays is given in Table 5.

TABLE 5. SUMMARY OF WOS DISPLAYS FOR FLIGHTS 851/852

851		852	
frame/step	WOS indication	frame/step	WOS indication
1/4	goalpost over aircraft marker (ACM)	1/4	same as 851
1/1-8/18	WOS level below ACM	1/4-9/3	WOS below ACM
8/19-11/8	WOS level climbs above ACM	9/4-11/8	WOS above ACM
11/9	WOS level drops	11/9	WOS drops less
11/10	WOS ***below*** ACM	11/10	WOS ***above*** ACM
11/11-15/11	WOS level always ***below*** ACM	11/11-15/11	WOS ***above*** ACM
15/12-17/7	WOS level above ACM	15/12-17/7	WOS above ACM
17/10-end	WOS level below ACM	17/10-end	same as 851

Analysis of the hovering turn portion of the flight (frames 1–2) reveals that turns of such a high rate are too great for the OASYS to compensate for. As illustrated in Figure 20, the window of safety display for frame one, step four (hereafter, 1/4) depicts a "goalpost" virtually on top of the aircraft marker (ACM). The presence of the goalpost indicates that the area to its left (in the direction of the turn) has not yet been scanned by the OASYS scanner.

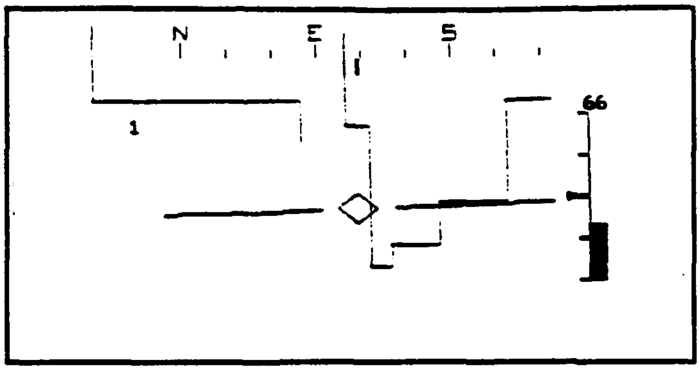


Figure 20. WOS Display From Frame 1, Step 4, Flight 851

However, this situation is expected and is not dangerous since the aircraft is merely turning about itself and is not translating. Also, for the majority of the turn, the goalpost does not appear close to the ACM in the display, indicating that the turn has been cleared at least in part by the OASYS.

Also of importance is the fact that even in such a high rate turn, accurate radar data was being collected throughout the turn. Figure 21 depicts the radar data processed during frame two. Note that the OASYS received consistent radar returns from the wires and even some returns from the vertical poles within range of the scanner. It is clear that although the resolution of the poles is decremented, the radar is detecting and locating obstacles within its range accurately, despite its large turn rate.

The real heart of this analysis centers on the remainder of the flight the downward pitching of the aircraft and the resulting acceleration. It is important to note that (as depicted in the graphs of Appendix B) the acceleration with corresponding pitch down occurs immediately upon reaching the desired heading; no time is allowed to pass while the aircraft is in a stabilized hover pointed in the direction of the acceleration.

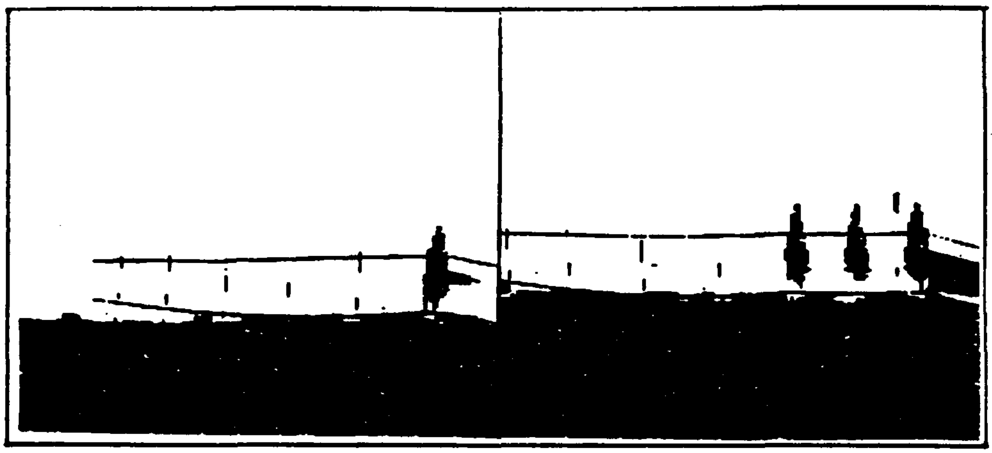


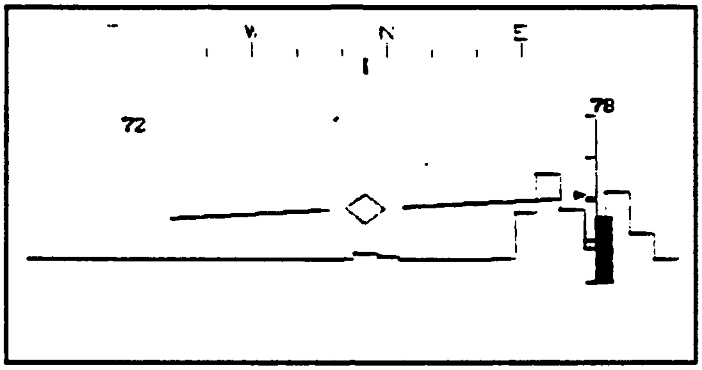
Figure 21. Processed Radar Data From Frame 2, Flight 851

The WOS displays for the first eleven frames for both flights are virtually identical. Small differences in individual frames are virtually insignificant and would generally be unnoticed by the pilot. However, from 11/9 through 17/7, the WOS displays are significantly different. In the control flight (852), the WOS display never depicts the aircraft marker above the WOS level at any time until frame 17. This indicates (as is clearly the case) that there are obstacles in the aircraft flight path throughout this time. However, flight 851's WOS displays depict the ACM *above* all obstacles for the period of the flight from 11/10 to 15/12. Thus a pilot flying with this display would believe that he was clear of all obstacles during these four frames, about six seconds, when clearly he is not.

Referring to Figure 18, which depicts the planview of the flights, it is apparent that the point at which differences begin to appear in the 2 WOS displays occurs immediately after crossing the 27 meter high trees (point B). The next set of obstacles that the OASYS should detect is the 34 meter high palm trees, the closest located approximately 350 meters from the initial

point of acceleration. The height of these trees above the aircraft flightpath and their relative proximity should cause the WOS display to rise rapidly above the ACM. This is exactly what happens in flight 852. Referring to Figure 22, it can be seen that flight 852's OASYS is detecting the large palm trees to its front, and provides a corresponding indication on the WOS display.

851



852

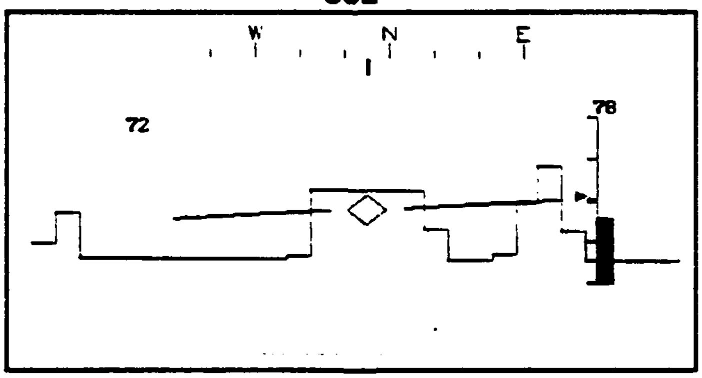


Figure 22. WOS Displays From Frame 11/18 of Flights 851/852

However, flight 851's OASYS produces WOS displays that do not agree with those of flight 852 and are inaccurate. The OASYS of flight 851 is unable to detect the *whole* tree and thus, as Figure 22 depicts, the WOS

display indicates smaller, incorrect images for the palm trees. As the flight progresses through frames 12, 13, and 14, the presence of the trees, which clearly pose a threat to the aircraft, is never relayed to the pilot through the WOS display. Finally, in 15/13 the WOS display begins to indicate the ACM below the WOS level, and by frame 17/7, the OASYS for flight 851 is again producing accurate WOS displays. This sequence is depicted in Figures 23 and 24.

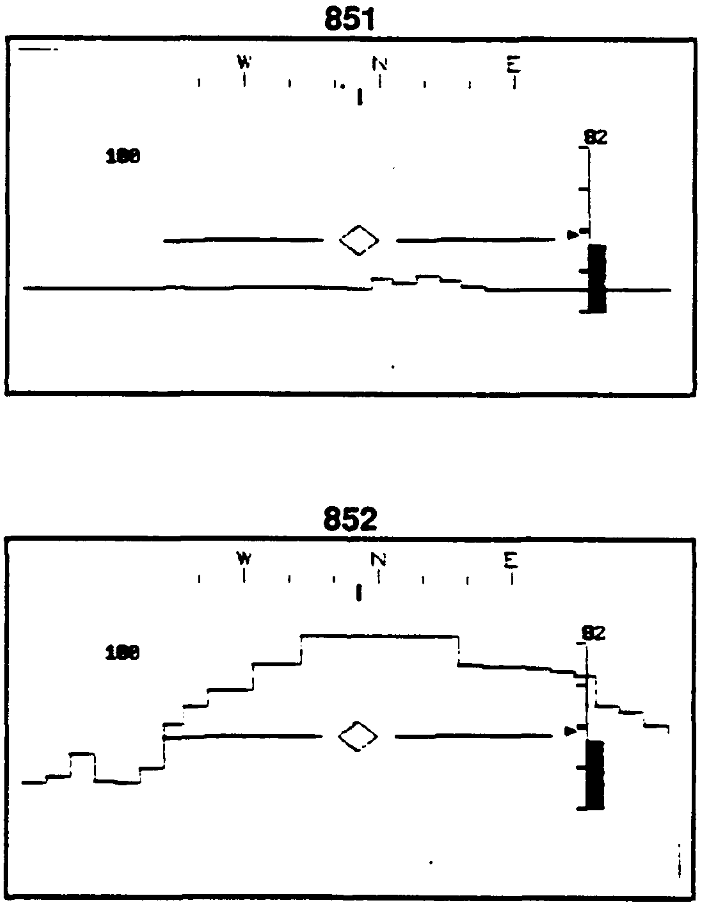


Figure 23. WOS Displays From Frame 14/15 of Flights 851/852

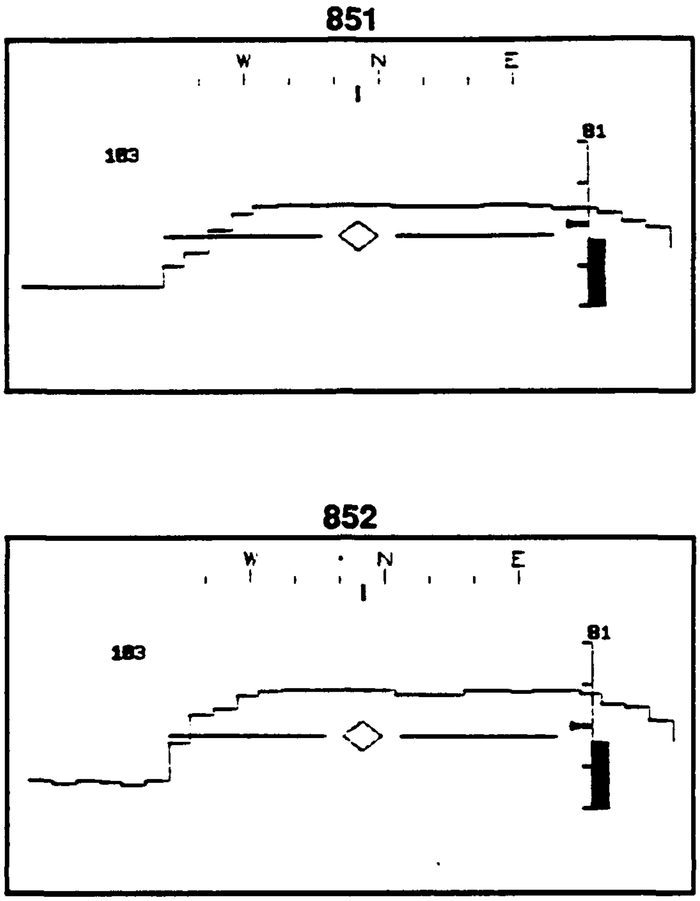


Figure 24. WOS Displays From Frame 17/7 of Flights 851/852

In analyzing the problem of flight 851's OASYS for frames 11-14, it is necessary to refer to Appendix B and study the dynamics of the aircraft. During the first 3 seconds of the pitch down maneuver, the aircraft transitioned from a pitch attitude of +2 to -12.5 degrees, while covering less than 50 meters. During these first three seconds, obstacles that were within range of the sensor were detected and their locations stored inertially. Thus, the near poles, wires, and trees were detected before the sensor exceeded its 12.5 degree vertical scan limit, and accurate information relative to these obstacles was provided in the WOS display until the aircraft was past these

objects. This explains why the WOS displays for the first eleven frames were almost identical.

However, after these first three seconds, because of the geometry of the sensor scan pattern, the sensor was blind to any new obstacles in the flight path of the aircraft. This situation persisted until the aircraft began to level off and reestablished a pitch down attitude of less than 12.5 degrees nose down, almost 15 seconds later. Thus, obstacles like the palm trees which were just outside the sensor's range initially, but entered the range of the scanner later, became undetectable after 3 seconds of acceleration.

The aircraft's rate of acceleration was such that the distance to these obstacles (palm trees) was covered before the aircraft pitched back up to maintain level flight (beginning in frame 14). The sensor was blind until frame 14 , at which time it had to complete a scan pattern, update its obstacle data base, and modify the WOS display before the obstacles were presented to the pilot.

This explanation is supported by two other observations. First, in juxtaposing 11/18 of both flights, it can be seen that the same two distinct areas of rising WOS level exist in each WOS display. These are clearly the same objects (palm trees) in both displays, but the WOS level for these trees in flight 852 is much higher than that for flight 851. The trees in flight 852's display are depicted accurately, but the tops of the trees in flight 851's display were cut off due to the pitching of the sensor during the acceleration. Thus, only the bottoms of these trees were detected and therefore, they appear shorter than they actually are. Their real height could not be determined or updated as the flight progressed because the sensor was blind until it was past them.

Further support is provided by examining Figure 25, which provides the corresponding radar plots of these flights. Note that frame 11 of flight 851 depicts the trunks of the palm trees, but the tops of these trees are cut off; again, this is because the pitching maneuver reduced the vertical coverage of the scan pattern. By contrast, frame 11 of flight 852 depicts the whole tree.

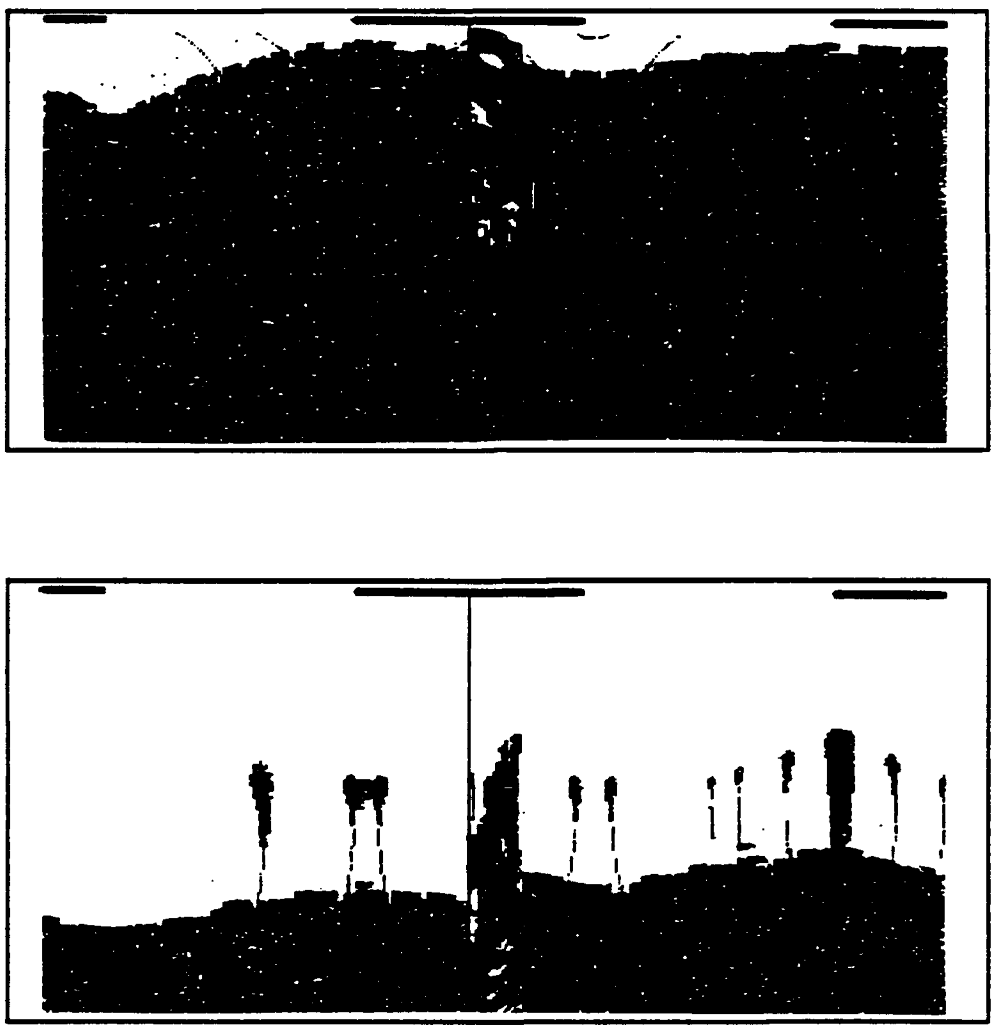


Figure 25. Processed Radar Data From Frame 11, Flights 851/852

9. Designing Follow-On Maneuvers

Follow-on flights were designed to develop a greater insight as to the limitations of the OASYS prototype. It appeared that the problem with the OASYS' effectiveness stemmed from the sensor's inability to detect some obstacles during the helicopter's pitch down motion associated with acceleration. Thus, parameters which would reduce the *time* for which the sensor experienced a reduced detection capability or the *degree* of the sensor's detection ability decrement could be manipulated in order to develop an envelope for the OASYS' effective operation. Therefore, several maneuvers were designed which incorporated modifications in these parameters, and then were analyzed using the same computer simulation.

The first of these maneuvers was designated flight 853. In this maneuver, the acceleration rate (and hence, the pitch down angle) was maintained consistent with that of flight 851, but the airspeed to which the aircraft accelerated before maintaining steady-state flight was reduced to 50 knots. Since the aircraft reached 50 knots within 10 seconds after initiating its acceleration (see pitch graph in Appendix D), the sensor was blind for a much shorter period of time and thus, the OASYS would in theory begin detecting objects again more quickly. A planview of flight 853 is given in Figure 26; note that the data base over which it was flown was the same as that for flight 851.

The second of these maneuvers, designated flight 854, again maintained the same acceleration as flight 851, but in this flight the aircraft only accelerated to 70 knots instead of 100 knots. The results of this flight should help to further define the flight envelope. Flown over the same data base as flight 851, this flight's planview is given in Figure 27.

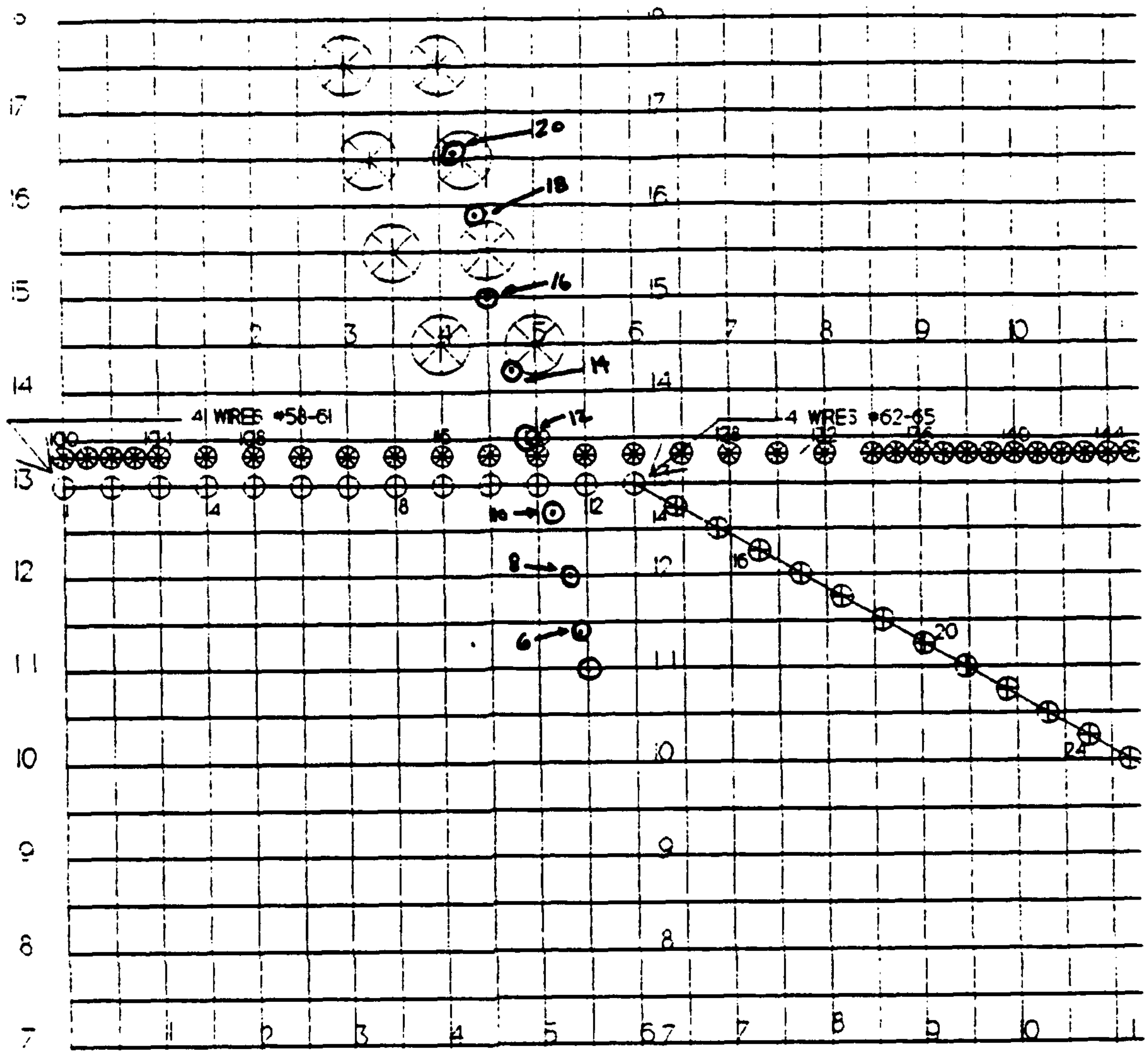


Figure 26. Planview of Flights 853/861

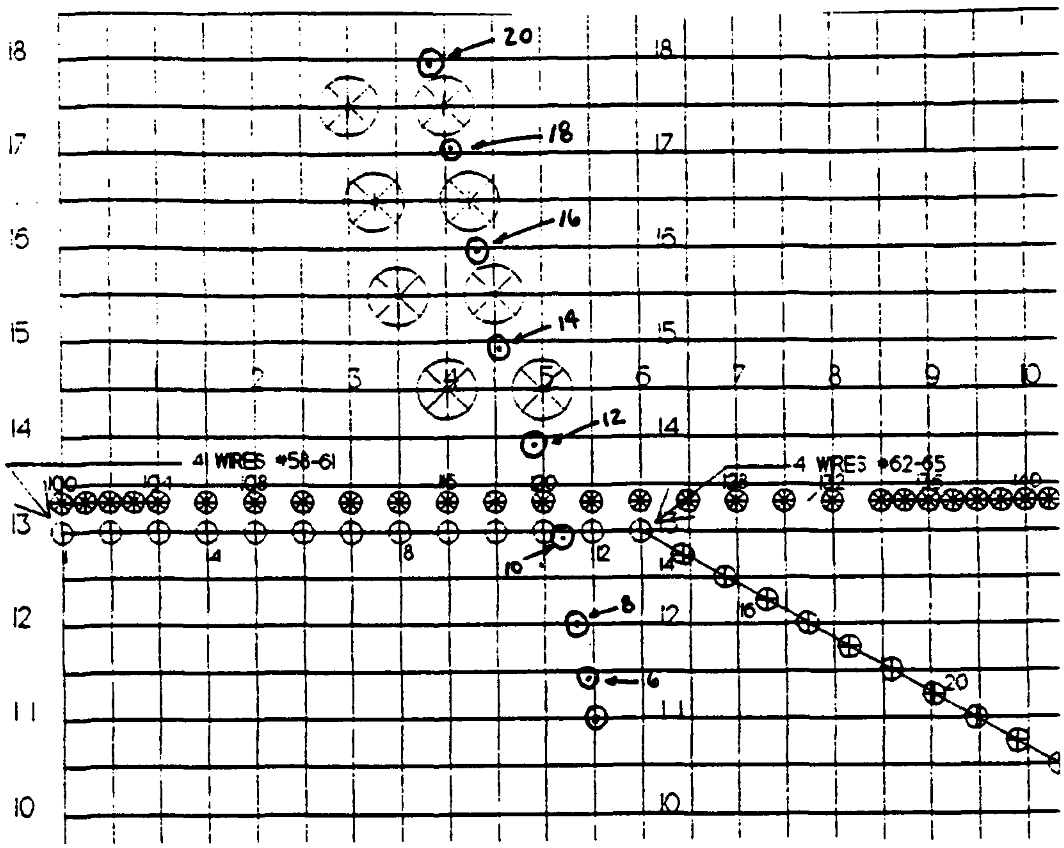


Figure 27. Planview of Flights 854/862

The final maneuver of this group, designated flight 855, modified flight 851 by changing the rate at which the aircraft accelerated. A lower acceleration rate of 1.5 m/sec^2 was substituted for the aggressive acceleration of flight 851. In accelerating at a reduced rate, the pitch angle maintained by the aircraft during the acceleration is reduced proportionately (this relation is described shortly). Thus, the sensor should be able to detect obstacles continuously throughout the flight, and should experience no decrement in performance due to the pitching maneuver. The planview of flight 855 is given in Figure 28.

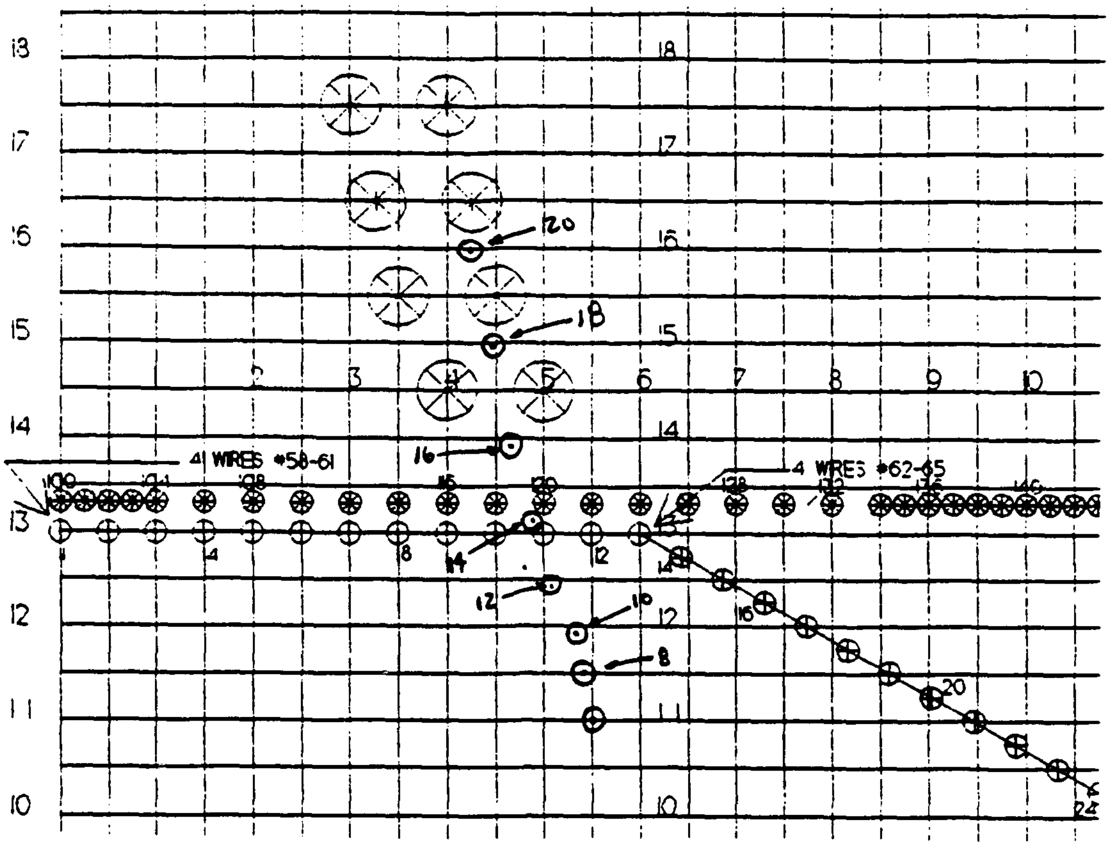


Figure 28. Planview of Flights 855/863

The time history parameters for flights 853-855 are given in Appendices D, F, and H, respectively. The plots for flights 853 and 854 were constructed exactly as the plots for flight 851 except that the pitch attitude was only maintained until the aircraft approached 50 and 70 knots, respectively. All other parameters were maintained as those in flight 851.

The time history plots for flight 855 were constructed as follows. All parameters with the exception of pitch attitude were maintained as those of flight 851. The pitch attitude plot (see Appendix H) reflects a pitch rate consistent with that of flight 851, down to a constant attitude of eight degrees. In order to maintain realism, the small perturbations about eight degrees were

incorporated by simply using the portion of the flight 851 pitch attitude plot which corresponded to maintaining a constant pitch attitude during the acceleration. This pitch attitude (including perturbations) was maintained throughout the 30 second flight; the airspeed achieved during the flight was 78 knots.

The angle to which the aircraft pitched during this flight was determined from an analysis of several of the time history plots recorded at the CSRDF. In analyzing these plots, it was determined that a direct relation existed between the acceleration rate and the pitch angle held during the acceleration. This relationship held in all of the acceleration maneuvers flown in the CSRDF and can be explained with reference to the following free body diagram.

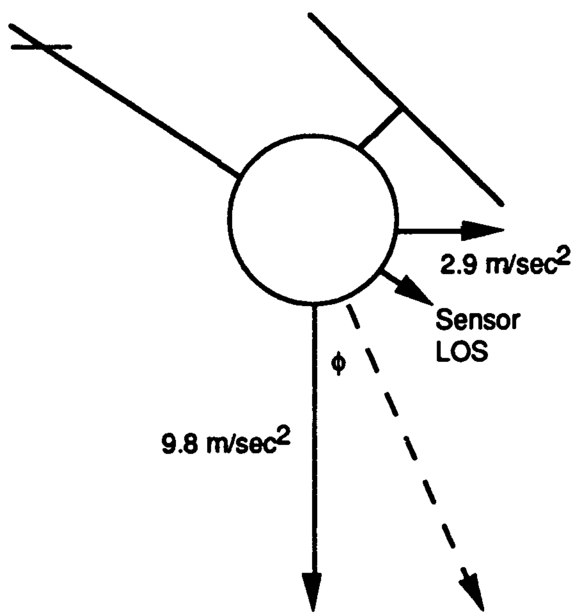


Figure 29. Free Body Diagram Showing Acceleration/ Pitch Angle Relationship

The angle ϕ that exists between the two orthogonal accelerations represents the pitch angle that the aircraft must maintain to achieve the linear horizontal acceleration desired. For example, to achieve an acceleration of 2.9 m/sec^2, the pitch angle must be maintained at:

$$\phi=\tan^{-1}(2.9/9.8)$$

$$\phi=16 \text{ degrees}$$

Referring to Appendix B, this is exactly the pitch angle (averaging out the small perturbations) maintained in the 2.9 m/sec^2 acceleration of flight 851. More gentle accelerations were flown in the CSRDF simulator, all of which provided similar correlation between pitch angle and rate of acceleration.

For these flights, new data files were constructed using the BES utility program. Then these flights were computer simulated over the same data base as existed for flight 851 using the BES OASYS simulator. As in flight 851, the first three seconds of each flight consisted of the rapid hovering turn. Comparing the planviews of these flights, it is obvious that their flight paths are all slightly different; this is expected since each flight progresses at different airspeeds.

Finally, as for flight 851, for each of these flights, a corresponding control flight, with pitch attitude maintained on the horizon throughout the flight, was generated and computer simulated. These flights were numbered 861, 862, 863, respectively corresponding to flights 853, 854, and 855. Comparisons of the ancillary flights with their controls should provide more insight on the limitations of the effectiveness of OASYS prototype.

10. Analysis Of Follow-On Flights

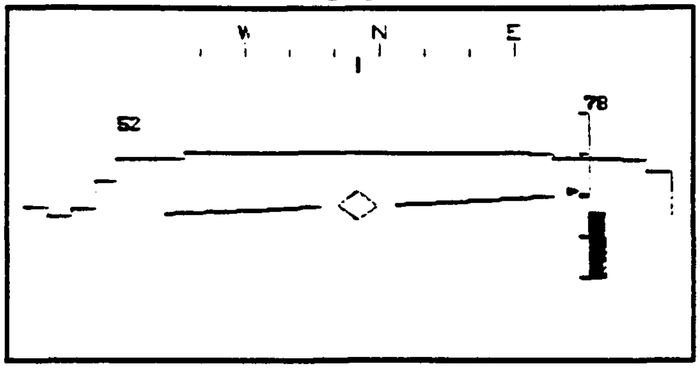
The WOS displays for flights 853 and 861 were stepped through individually on adjacent computer monitors so that exact comparisons could be made between the two flights' displays. Based on the time history plot of flight 853, it seemed intuitive that since the aircraft pitch attitude remained more than 12.5 degrees down for only an approximate five seconds, the OASYS could provide accurate obstacle avoidance information throughout the maneuver. The results of comparing the two flights, as well as the other ancillary maneuvers, follows.

The WOS displays for each flight were virtually identical through frame 9/2. After this frame, slight differences in the two WOS displays began to appear. For example, in frame 11/20 (Figure 30), it is clear that the OASYS of flight 853 is not providing information about obstacles on the left fringe of the display. Also, the WOS display provided by the flight 861 (control) OASYS is slightly higher than that provided by the OASYS of flight 853. This trend is again noted in frame 13/6, in which the right fringe of the WOS for flight 853 depicts a "cut-out" area in the window of safety, which does not appear in the display for flight 861.

Another interesting difference occurs in frame 14/4 (Figure 31). The WOS display for flight 853 is actually *higher* than that provided by the control flight. By frame 17/6, the two flights are producing identical WOS displays again, and this is maintained throughout the remainder of the flights.

Overall, the slight inconsistencies in the WOS displays are insignificant and in general, the WOS height with respect to the ACM, especially near the center of the display, is virtually identical throughout the flights.

853



861

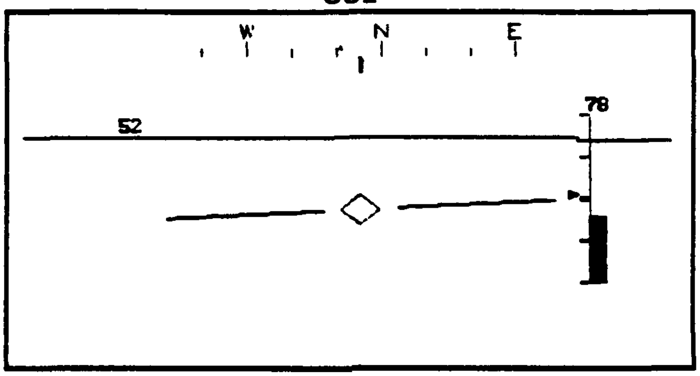


Figure 30. WOS Displays of Frame 11/20 From Flights 853/861

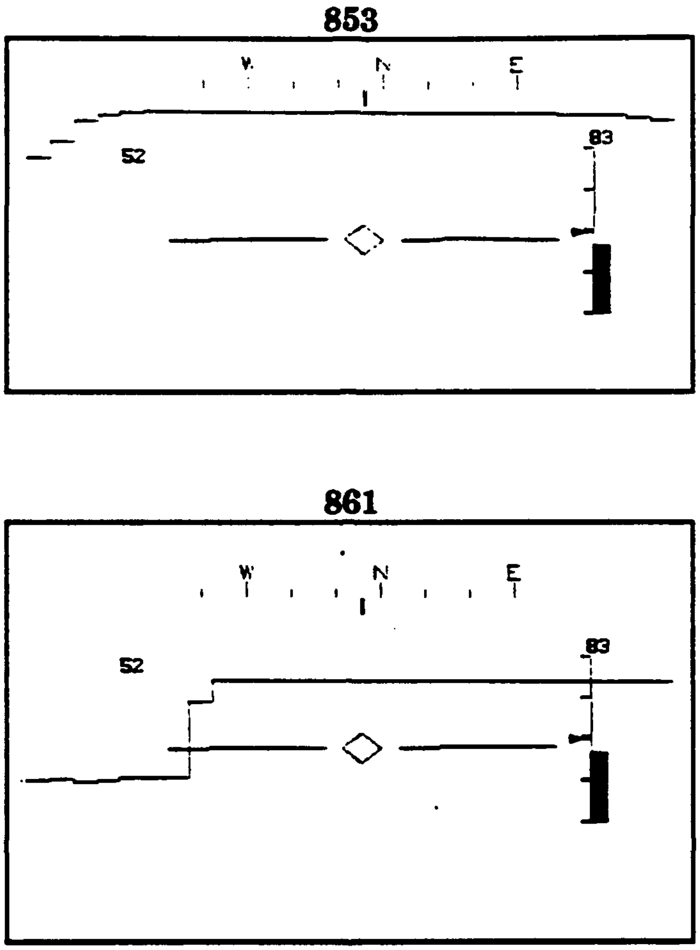
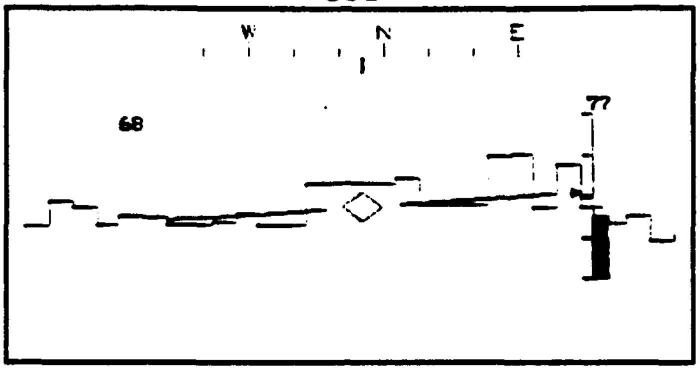


Figure 31. WOS Displays of Frame 14/4 From Flights 853/861

Flights 854 and 862 were compared in the same manner as flights 853 and 861, with similar results. Again, on the fringe of the two flights' WOS displays, slight differences are present (Figure 32); in fact it is generally flight 854's WOS display which seems to provide more indications of obstacles along the fringes of the display. However, at the center of the display, the location of the WOS with respect to the ACM is virtually identical in both flights; although minor differences exist in the displays, the differences are insignificant.

854



862

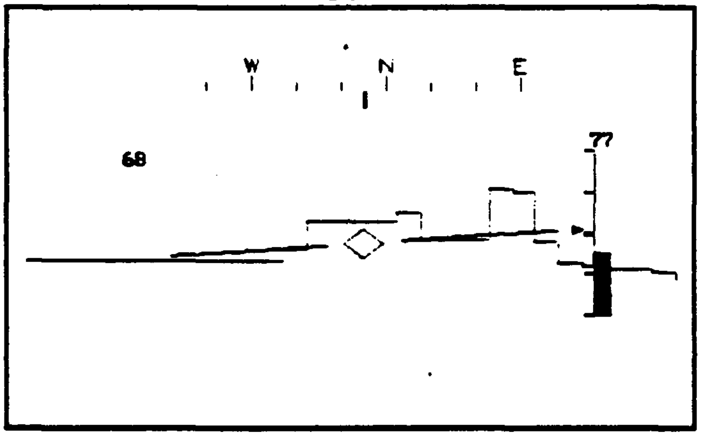


Figure 32. WOS Displays of Frame 11/10 From Flights 854/862

These two flights' displays also exhibit the phenomenon observed in flights 853/861, in which the WOS of the non-control flight was actually *higher* than that of the control flight (Figure 33).

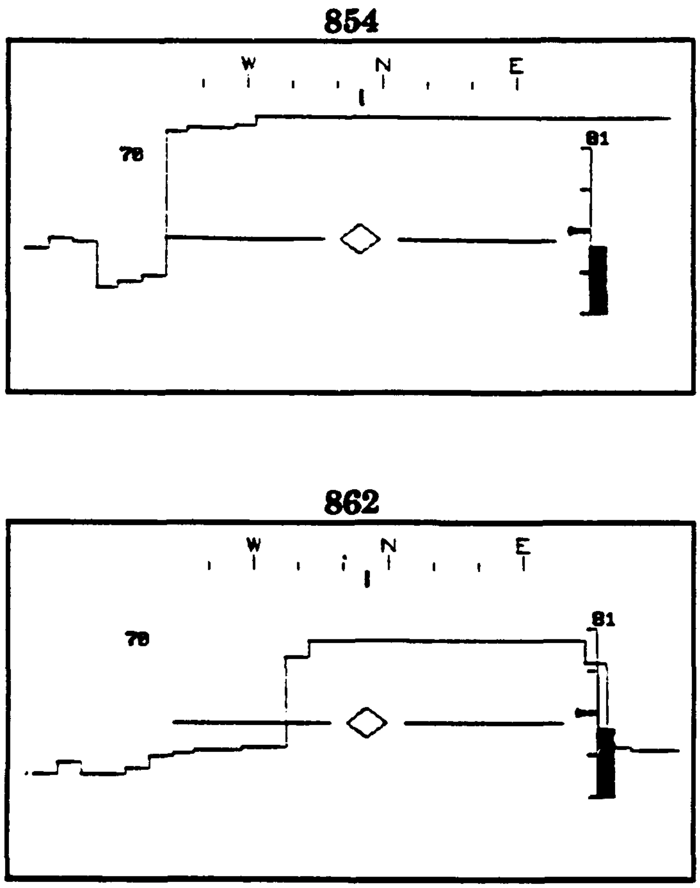


Figure 33. WOS Displays of Frame 15/14 From Flights 854/862

Flights 855 and 863 were also compared as before and produced similar results. The differences in the WOS displays for these two flights were even less significant than those of the previous ancillary flights. Figure 34 depicts the frame in which the greatest difference in the two flights' displays occurs. On the fringes of the displays, there are minor differences, but in the center of the display, the indications are virtually exact. Again, the unexpected phenomenon of the non-control flight's providing a higher WOS indication at a few points in the flight was observed.

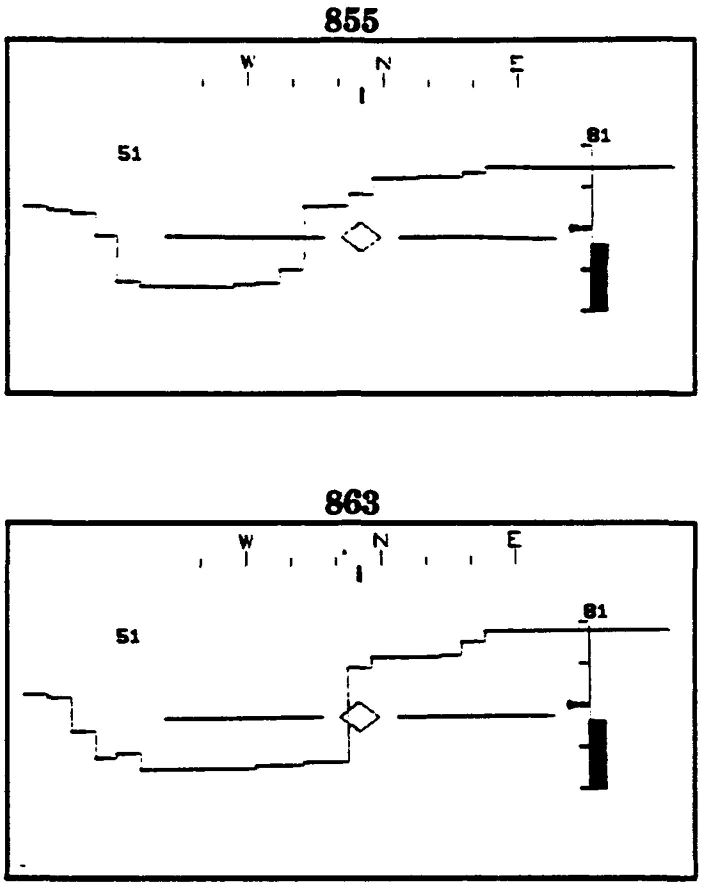


Figure 34. WOS Displays of Frame 15/1 From Flights 855/863

The results of these three follow-on flights were generally consistent and expected. The flights demonstrated that by reducing the terminal airspeed or the acceleration rate, the OASYS could provide generally consistent, accurate WOS displays.

The unexpected phenomenon that was noted in each flight, especially at the fringes of the display, is probably explained by an examination of the sensor scan pattern, the dynamics of the aircraft, and the method of processing radar returns. When the aircraft pitches down, the portion of the scan pattern that detects the objects is transferred to higher on the scan circle. The distortion that exists high on the scan circle and granularity

induced by the processing, introduces slight errors in object position. These slight errors in the location of the object result in a slightly altered WOS display. Because these position errors are random and very minor, the altered display is insignificant and random. Thus, the WOS display for the control flight is sometimes slightly higher than that of the non-control flight, and sometimes slightly lower.

11. Results Of Phase I

The results of phase I are summarized in Table 6.

TABLE 6. RESULTS OF PHASE I

FLIGHTS	TERMINAL AIRSPEED (kts)	ACCELERATION (m/sec^2)	RESULTS
851/852	100	2.9	significant differences in WOS
853/861	50	2.9	insignificant differences in WOS WOS height at center equal
854/862	70	2.9	insignificant differences in WOS slightly more differences than exist in 853/861
855/863	78	1.5	insignificant differences in WOS displays are almost exact

B. PHASE II

The results of Phase I provided insight and understanding of the problems inherent in the fix-mounted OASYS prototype currently in fabrication at Northrop. This phase will expand that understanding by applying mathematical procedures to the conclusions developed in Phase I and will

ultimately result in the generation of an envelope of flight parameters for which the OASYS prototype will provide accurate obstacle avoidance information [Ref. 8].

The following variables are defined for this analysis:

R= the radar range of the OASYS (meters)

V= velocity to which the aircraft will accelerate (m/sec)

D= the distance traveled during the acceleration (meters)

T= the time for the aircraft to accelerate to terminal velocity (sec)

A= constant acceleration rate for the flight (m/sec^2)

Z= the reaction time required by the pilot to avoid an object (sec)

The distance traveled during a constant rate acceleration is given by the product of the average velocity and the elapsed time during the acceleration. Since the aircraft's initial velocity will be zero throughout this analysis:

$$D = (V/2) * T \tag{1}$$

Likewise, the time required for the aircraft to accelerate to a given velocity is given by:

$$T = V/A \tag{2}$$

Based on the results of Phase I, the OASYS prototype can be assumed to provide effective obstacle avoidance information if the range of the sensor is greater than the following combined distances: (1) the distance covered during the acceleration, (2) the distance that is covered in the time that it takes the OASYS scanner to complete one scan across the front of the aircraft, process the data and provide the WOS display, and (3) the distance covered during the time it takes the pilot to react to the obstacle information in the WOS

display. Distance (2) is included with the assumption of a worst case scenario in which the aircraft completes its acceleration with the scanner in the worst position for detecting the object to its front; this time is taken to be 0.75 seconds since the processing time is negligible.

The above statements may be expressed algebraically by:

$$\text{OASYS effective if:} \qquad R > D+(Z+.75)*V \tag{3}$$

By setting equation (3) to the limiting case where the radar range exactly equals the three combined distances, and substituting equation (1) into equation (3), the following equality results:

$$V/2*T+(Z+0.75)*V=R \tag{4}$$

Substituting equation (2) into equation (4) and rearranging yields:

$$V^2+(Z+.75)*2A*V-2AR=0 \tag{5}$$

This quadratic may be solved for V using the quadratic formula to give:

$$V=-(Z+.75)*A +/- (.5)*(4A^2*(Z+.75)^2+8AR)^{1/2} \tag{6}$$

Taking the positive root of this equation yields the velocity to which the aircraft may accelerate at a constant rate and remain within the effective envelope of the OASYS.

Making the assumption that the minimum reaction time that a pilot requires to affect an obstacle avoidance maneuver is approximately two seconds [Ref. 2], simplifies equation (6) to:

$$V=-2.75A+.5(30.25A^2+8AR)^{1/2} \tag{7}$$

Thus, the envelope for effective operation may be reduced to three variables: the range of the sensor, the acceleration rate (and hence, the pitch angle) and the velocity to which the aircraft accelerates. Given a fixed detection range, such an envelope of two variables may be defined by solving equation (7) for V for several values of A and plotting the results. For the radar range used in this simulation (300 meters), the envelope is depicted in Figure 35. Note that the bottom limit of the envelope is defined by equation (7).

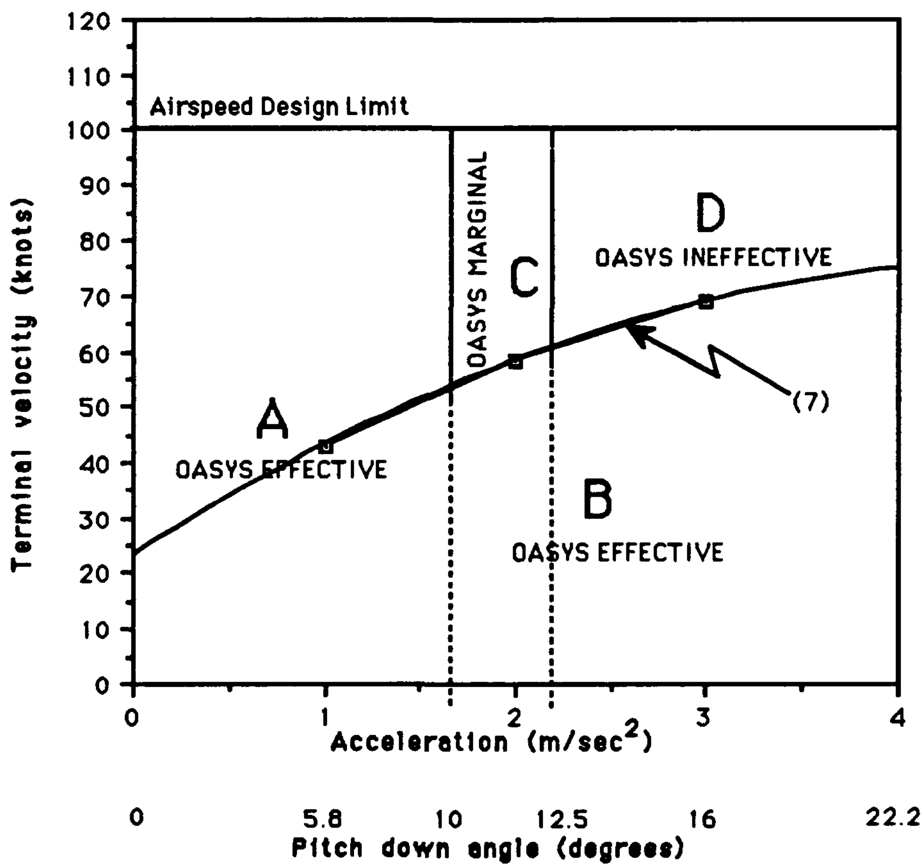


Figure 35. Flight Envelope of OASYS Prototype During Acceleration Maneuvers

In analyzing Figure 35, four distinct areas are clearly defined. Areas A and B represent the loci of combinations of terminal airspeeds and acceleration rates (pitch angles) for which the OASYS will be completely effective during a level acceleration. In area A, the aircraft never reaches a pitch down attitude low enough to impair the sensor's effectiveness at any time during the flight. In area B, although the aircraft pitches to an attitude that could impair the sensor, the airspeed to which the aircraft accelerates is slow enough that the terminal airspeed is reached before the sensor range is outrun. An example of a flight in this region is flight 853.

Area C represents an area of marginal effectiveness for the OASYS. In this region, the limits in acceleration are defined by those corresponding to the 12.5 degree sensor limit in pitch, and an arbitrarily chosen value of 10 degrees. This value was chosen to demonstrate that although the sensor is not completely blind until the 12.5 degree limit, the quality of the radar data is somewhat reduced for pitch angles in this neighborhood. Thus, the information presented to the pilot for a flight in this region may not be exact. The basis for this conclusion is the results of flight 855, which remained in area B, but gave indications of less than optimal performance of the OASYS.

Area D represents the region of high acceleration (large pitch down angles) to high airspeeds in which the OASYS prototype is ineffective. An example of a flight in this region is flight 851.

Figure 35 represents the OASYS operational envelope with a fixed sensor detection range of 300 meters. If the range of the sensor is varied, the envelope changes. Figure 36 depicts the effects of sensor range on the size of the envelope for effective OASYS operation. With increasing values of sensor range substituted into equation (7), the curve in Figure 35 is shifted upwards

to effectively increase the envelope of maneuvers for which the OASYS is effective and correspondingly decrease the size of the envelope for which it is ineffective.

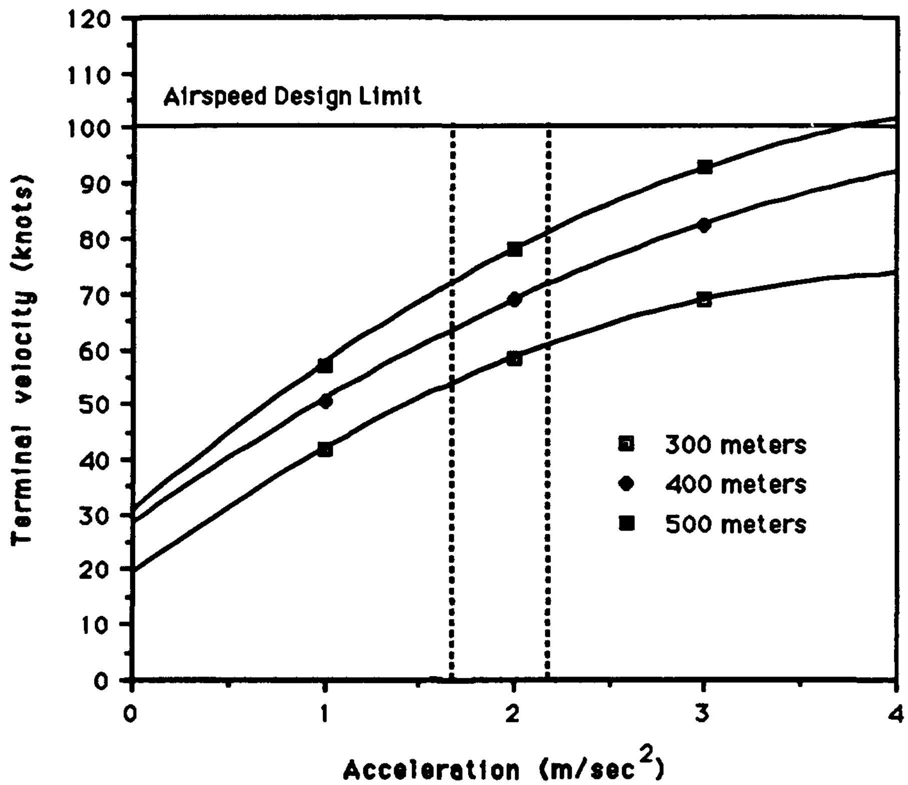


Figure 36. Effect of Sensor Range on OASYS Flight Envelope

C. PHASE III

The purpose of Phase III was to validate the envelope designed in Phase II. Multiple computer simulations with varying terminal airspeeds and accelerations were conducted on a flight specifically designed to eliminate all other variables. Also, a data base was designed such that results determined on it could be generalized to any situation. These flights are described in Table 7;

the results of these flights empirically verified the flight envelope of the OASYS prototype defined in Phase II.

TABLE 7. DESCRIPTION OF PHASE III FLIGHTS

FLIGHT	TERMINAL AIRSPEED	ACCELERATION	RESULTS/COMMENTS
856	100	2.9	control for 857
857	100	2.9	ineffective OASYS, major errors
858	50	2.9	effective OASYS, no errors
859	70	2.9	effective OASYS, slight errors
860	78	1.5	effective OASYS, no errors
864	80	2.9	ineffective OASYS, significant errors
865	97	2.0	effective OASYS, slight errors
866	100	2.4	ineffective OASYS, significant errors
867	75	2.9	marginally effective OASYS, more than slight errors, borderline case

The flight simulations in Phase III were developed specifically to produce results which eliminated many variables associated with the rather random selection of the data base used in Phase I. The flight parameters determined in the CSRDF and used in the previous flights were again used to develop the flight profiles for each flight, but were manipulated and controlled much more in order to produce the exact conditions sought in each flight. Each of these flights began at a stabilized hover for three seconds at an altitude equal to a datum line. From this point, the aircraft began a horizontal acceleration at a fixed rate (e.g., flight 856's acceleration rate was 2.0 m/sec^2). Also, at this point, the aircraft began a vertical acceleration at a fixed rate equal to exactly 1/20th of the horizontal rate. This ratio was maintained a constant

throughout the flight and was based on the orientation of the obstacles in the data base.

As the aircraft climbed and accelerated, the heading, roll, and drift velocity parameters were maintained as recorded at the CSRDF, thereby ensuring that as much realism as possible was achieved. The X, Y, and Z parameters were determined as functions of time by a utility program that accepted accelerations in the three axes as inputs. The parameter that was again key to this analysis was the pitch parameter, which was manipulated as in Phase I to produce a pitch time history plot consistent with the terminal speed and acceleration rate of the aircraft.

The obstacle data base for these flights consisted of several sets of poles with 3/8 inch wires mounted across the tops, oriented perpendicular to the flight path of the aircraft. The first of these poles was located at a distance of 100 meters from the initial point of the aircraft's acceleration and subsequent poles and wires were located at 50 meter increments. The height of the first pole/wire was five meters above the datum line, and the height of the subsequent pole/wires was increased at 2.5 meter increments. Thus, the slope of a line that connected the tops of the obstacles was 1/20, the same as the ratio of the vertical and horizontal acceleration rates. The profile view of a generic flight path for a Phase III flight is given in Figure 37.

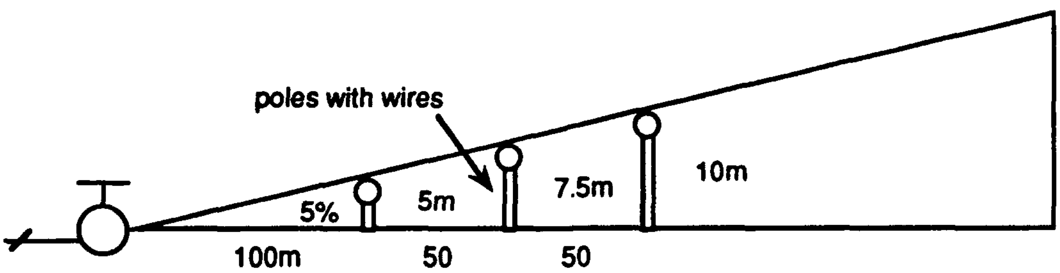


Figure 37. Profile View of Generic Phase II Flight

The theory involved in developing this flight scenario and data base follows. The WOS calculation algorithm contains a term comprised of the ratio of the vertical and horizontal velocities. In the WOS display calculation, this term is subtracted from the remainder of the expression. The algorithm is written such that when the difference of these two parts of the expression equals zero, the corresponding window of safety level is depicted equal to the height of the ACM, indicating that the aircraft will clear the obstacle by the preset distance; for these flights, the preset distance was one meter. During each flight, the ratio of the horizontal and vertical accelerations and velocities was held constant and the aircraft was programmed to fly a flight path that would result in its clearing the obstacles by the one meter. Thus, these flights *were designed to cause the WOS level to rise to the level of the ACM and to remain there for the duration of the flight as long as the OASYS is operating properly. If the WOS did not remain at the level of the ACM, it could be concluded that the OASYS was ineffective in detecting all of the obstacles along the flight path.*

In analyzing the phase III flights, if the WOS level climbed to the level of the ACM and remained there for the duration of the flight, then the OASYS was termed "effective" for that flight. If significant drops in the WOS display (greater than two seconds of flight time) were experienced, the OASYS was termed "ineffective" for that flight. As expected, the OASYS produced "marginal" results for some flights (e.g., flight 867). During these flights, the WOS dropped for a short time and was generally ragged or sawtoothed for some period of the flight, thus indicating that less than optimal information was being provided to the pilot.

Figure 38 is a replica of Figure 35, but includes the data points flown in flights during Phase III. The results of the Phase III flights clearly validate the analytical model derived in Phase II except in the case of flight 859. Based on the Phase II analysis, the OASYS of flight 859 should be less effective than it appeared to be during the actual Phase III simulation. Despite a few errors in the WOS displays, flight 859's OASYS provided accurate WOS information throughout the flight. Flight 867 (same acceleration/pitch attitude, but terminal speed five knots greater) is the borderline case at that acceleration rate.

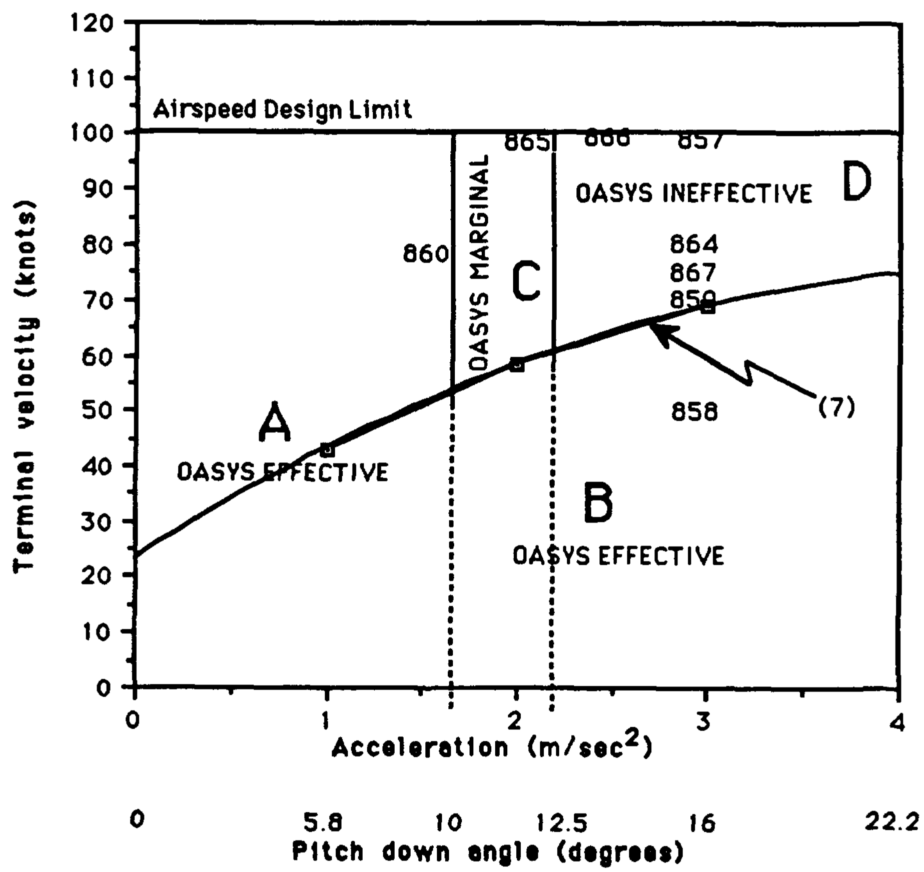


Figure 38. Flight Envelope of OASYS With Phase III Flights Included

IV. CONCLUSIONS

The following conclusions may be drawn from this study.

1. Results show that this OASYS prototype is an effective system for providing adequate warning of impending wire (or other obstacle) strike for the hypothetical case of a helicopter flying over a prescribed course at zero pitch attitude (flight 852).

2. Results show that this OASYS prototype has blind regions for obstacle strike warning when subjected to representative pitch rates and pitch attitudes over a prescribed course of flight (flight 851).

3. The primary purpose of this research has been to define the limits of the OASYS prototype by conducting simulated flights in the U.S. Army's CSRDF at Ames Research Center and providing pitch, pitch rate, and other flight information to the OASYS prototype simulator of BES Engineering.

4. There exists a flight envelope as depicted in Figure 35 that generally defines the functional limits of the OASYS prototype in accelerating flight, given an assumed required reaction time. It is important to note that there are areas in which the OASYS prototype is completely effective and areas in which the OASYS prototype is completely ineffective. The area for which the OASYS prototype is ineffective may be reduced by increasing the range of the sensor.

5. The envelope of effective operation of the OASYS during an acceleration is a complex function of many parameters, including sensor range, pilot reaction time, the acceleration rate (pitch attitude held during the acceleration) and the terminal airspeed of the aircraft.

6. This envelope is not exact due to situational differences associated with obstacles in the flight path, aircraft altitude, aircraft design, etc. This fact is highlighted by the presence of the marginally effective area depicted on Figure 35. More research is necessary to more accurately define the trade-offs in these operational variables to ensure that the OASYS is capable of performing to the required specifications.

7. For a 2.9 m/sec^2 level acceleration to 100 knots over the data base described, the fix-mounted OASYS prototype without pitch axis freedom does not provide accurate obstacle avoidance information throughout the flight. There is a period of several seconds during which the OASYS does not provide information on the palm trees located outside the initial range of the sensor. The addition of pitch axis stabilization corrects this defect completely as is demonstrated in flight 852.

8. Certain granularities in processing caused by the interaction of the sensor's scan pattern with the aircraft dynamics, resulted in object distortion along the top of the scan circle. This also reduced the level of precision attained in the envelope plot.

9. The sensor itself functions properly during straight and level flight and during accelerations up to 100 knots. The addition of pitch axis

stabilization eliminates acceleration induced (*pitch* induced) problems with the OASYS prototype system.

10. Object data was found to be adequately collected during hovering turns at rates of 43 degrees/second.

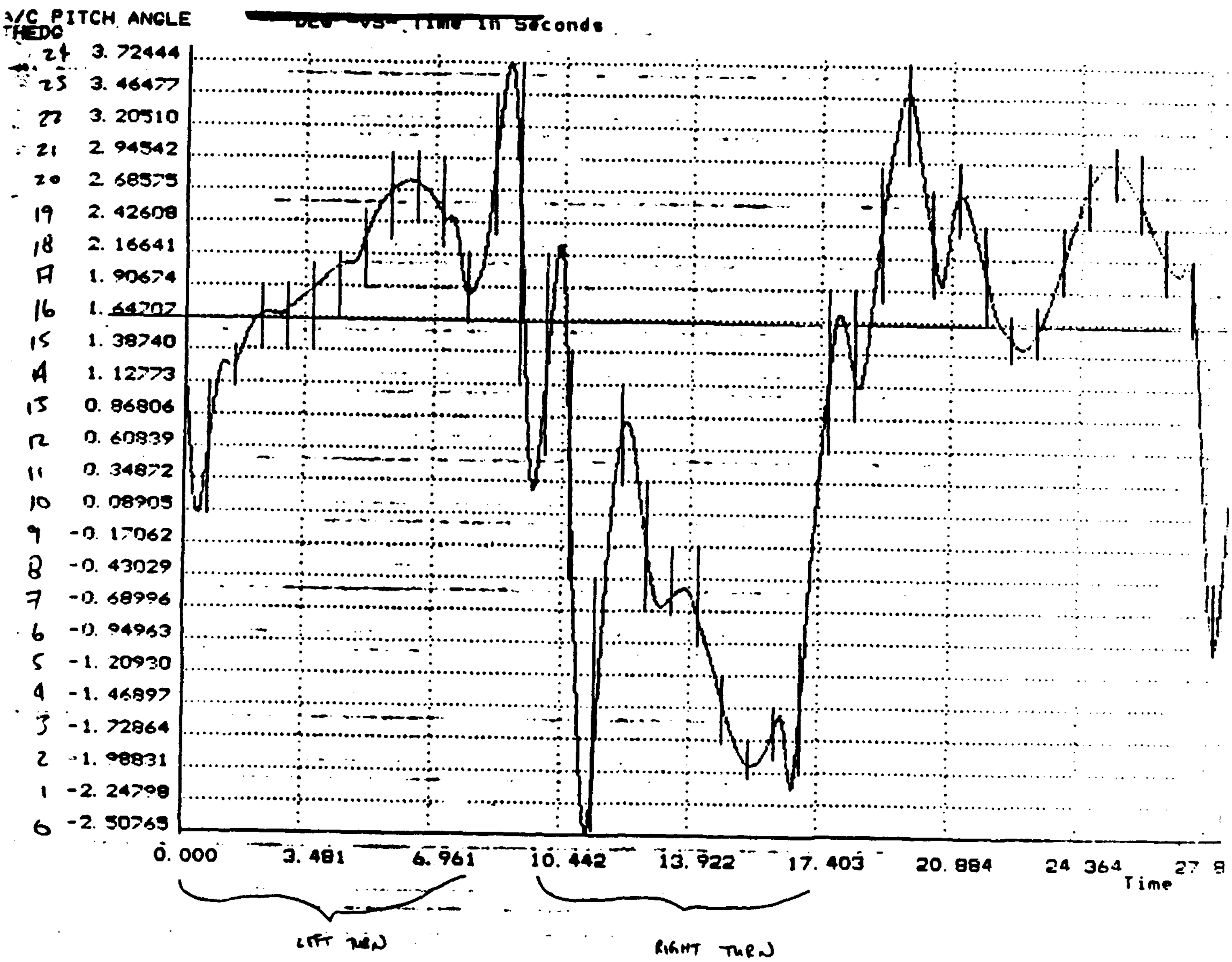
V. RECOMMENDATIONS

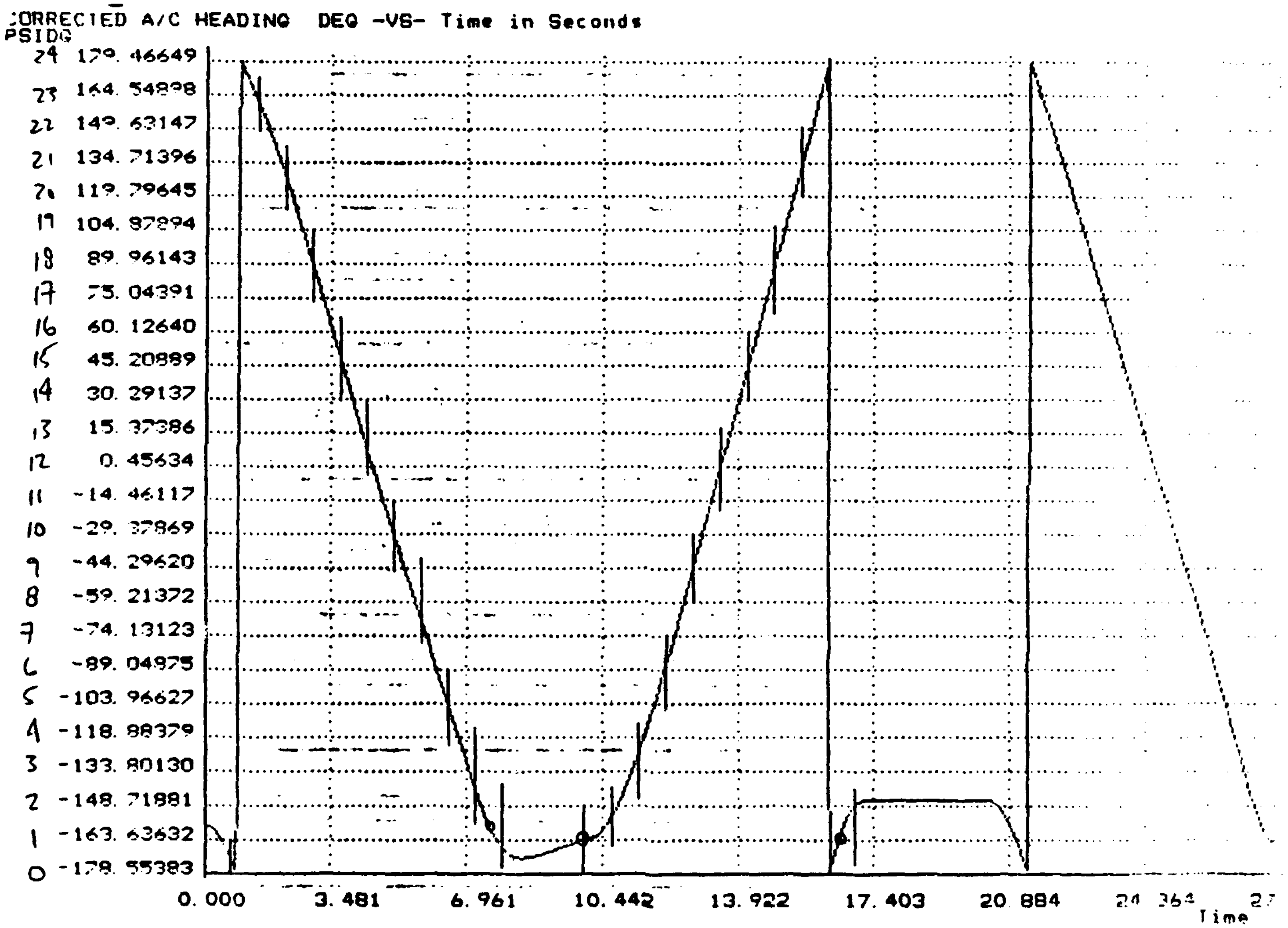
In any future procurement of OASYS, the system specification should include a requirement for reliable Ladar data collection during maneuvers about the pitch axis such as level accelerations. Pitch axis control or stabilization in the form of a pitch gimbal system or a pitch prism should be incorporated before flight testing of the present OASYS prototype is conducted. If this is not possible, pitch maneuvers should be limited to 10 degrees or should be limited in time if the 10 degree limit is exceeded during the flight.

Despite some limitations, OASYS' potential for increasing the safety margin during helicopter operations is unquestionable, and therefore, studies involving this system should continue to be conducted. Future studies should include evaluating system effectiveness in other maneuvers such as pitch up maneuvers (decelerations), ridgeline crossings, and descents into landing zones. Further studies could also involve investigating means of expanding the maneuver envelope of the OASYS prototype through varying the size or shape of the scan pattern, changing the control laws of the scan rate, or increasing the range of the sensor.

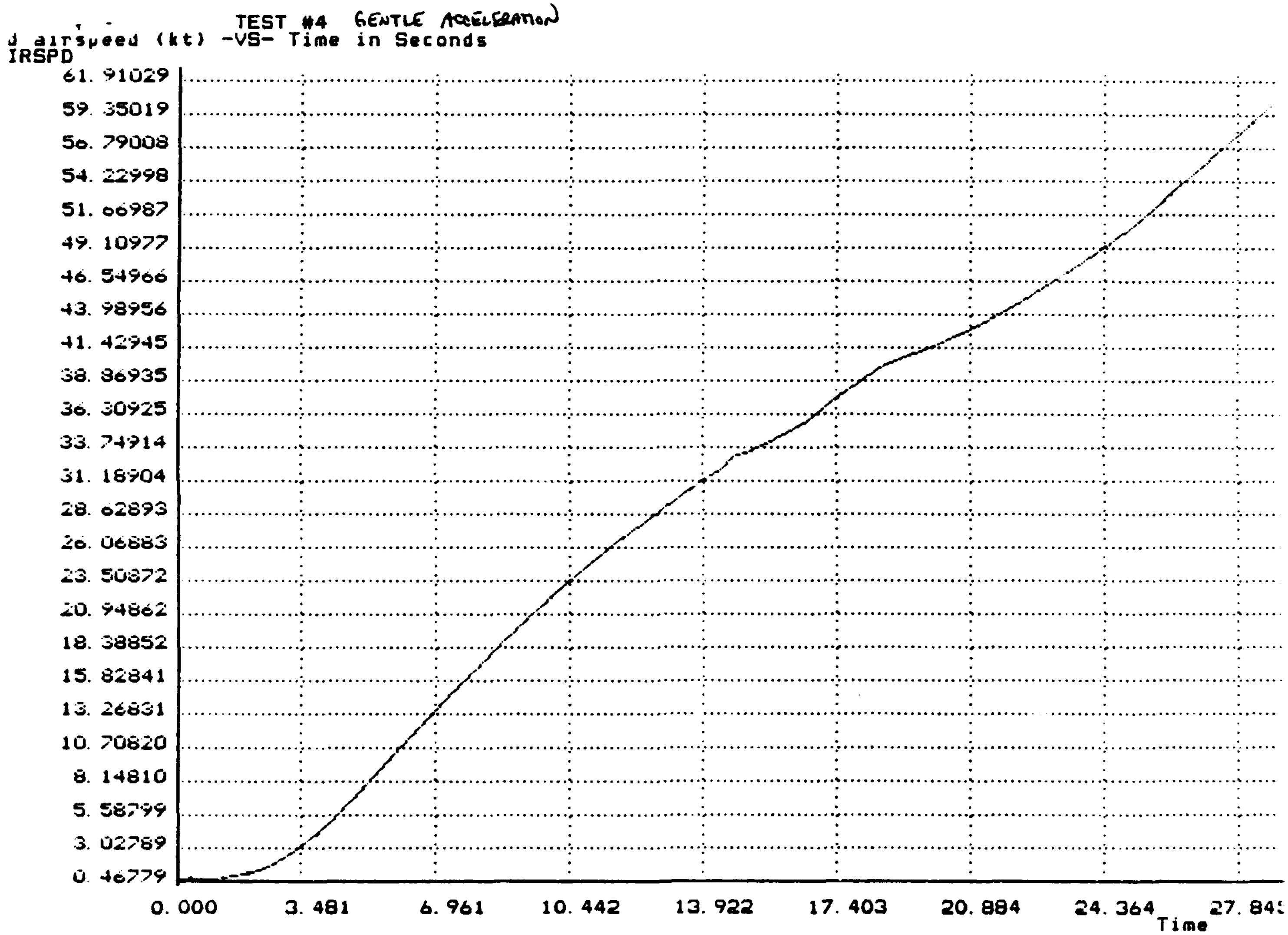
APPENDIX A

SELECTED TIME HISTORY PLOTS FROM ORIGINAL CSRDF FLIGHTS



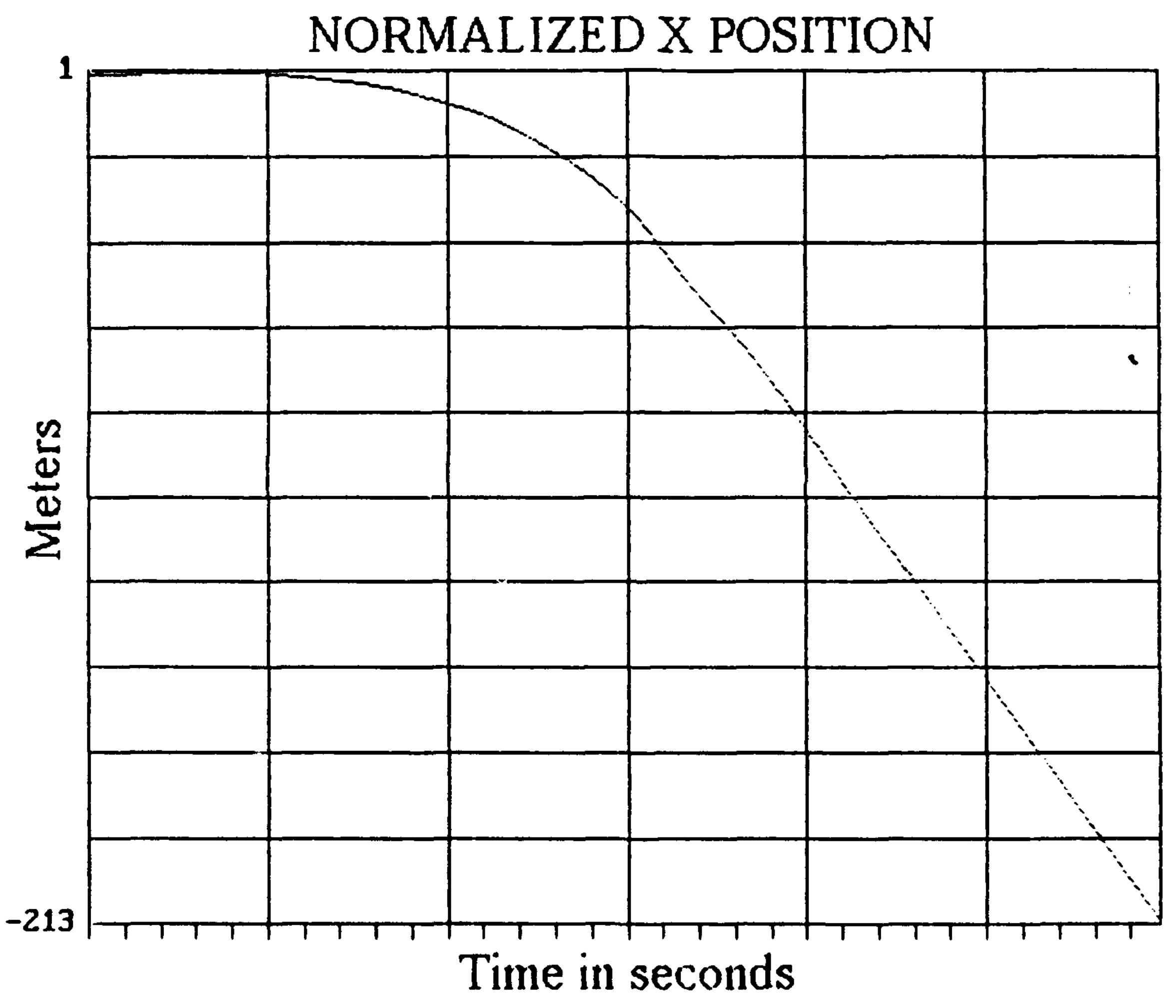


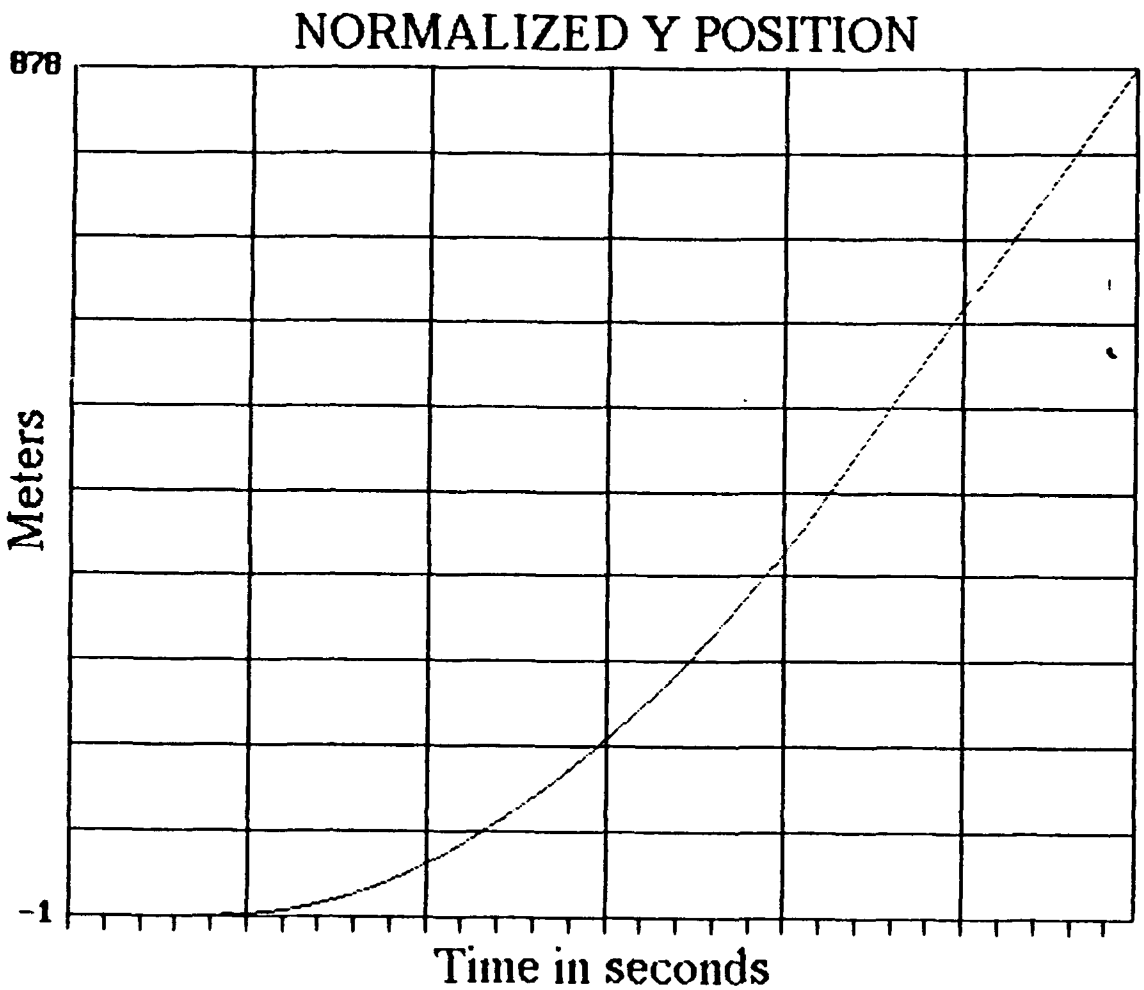
CORRECTED A/C HEADING DEG -VS- Time in Seconds
PSIDG
24 179.46649
23 164.54898
22 149.63147
21 134.71396
20 119.79645
19 104.87894
18 89.96143
17 75.04391
16 60.12640
15 45.20889
14 30.29137
13 15.37386
12 0.45634
11 -14.46117
10 -29.37869
9 -44.29620
8 -59.21372
7 -74.13123
6 -89.04875
5 -103.96627
4 -118.88379
3 -133.80130
2 -148.71881
1 -163.63632
0 -178.55383
0.000
3.481
6.961
10.442
13.922
17.403
20.884
24.364
Time

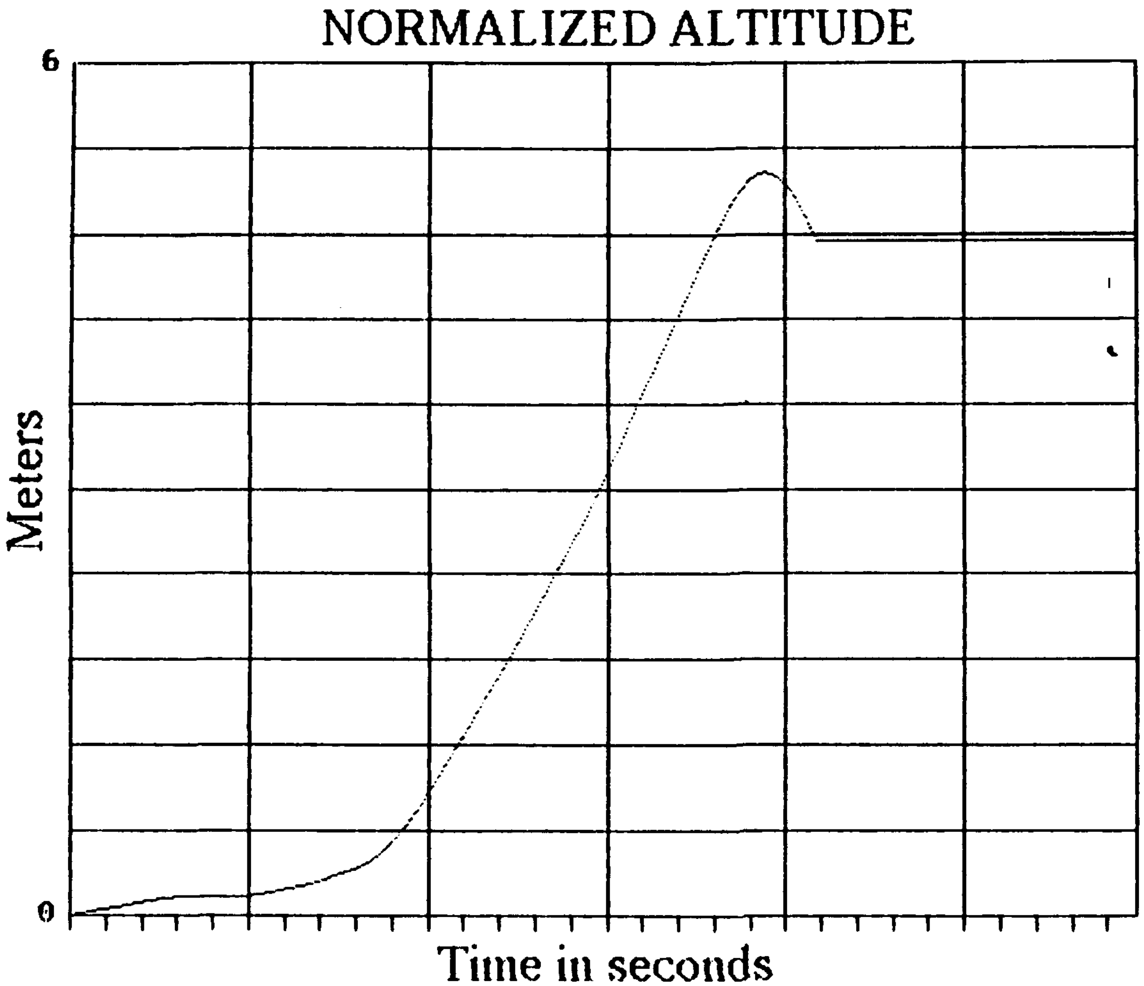

TEST #4 GENTLE ACCELERATION
d airspeed (kt) -VS- Time in Seconds
IRSPD
61.91029
59.35019
56.79008
54.22998
51.66987
49.10977
46.54966
43.98956
41.42945
38.86935
36.30925
33.74914
31.18904
28.62893
26.06883
23.50872
20.94862
18.38852
15.82841
13.26831
10.70820
8.14810
5.58799
3.02789
0.46779
0.000
3.481
6.961
10.442
13.922
17.403
20.884
24.364
Time

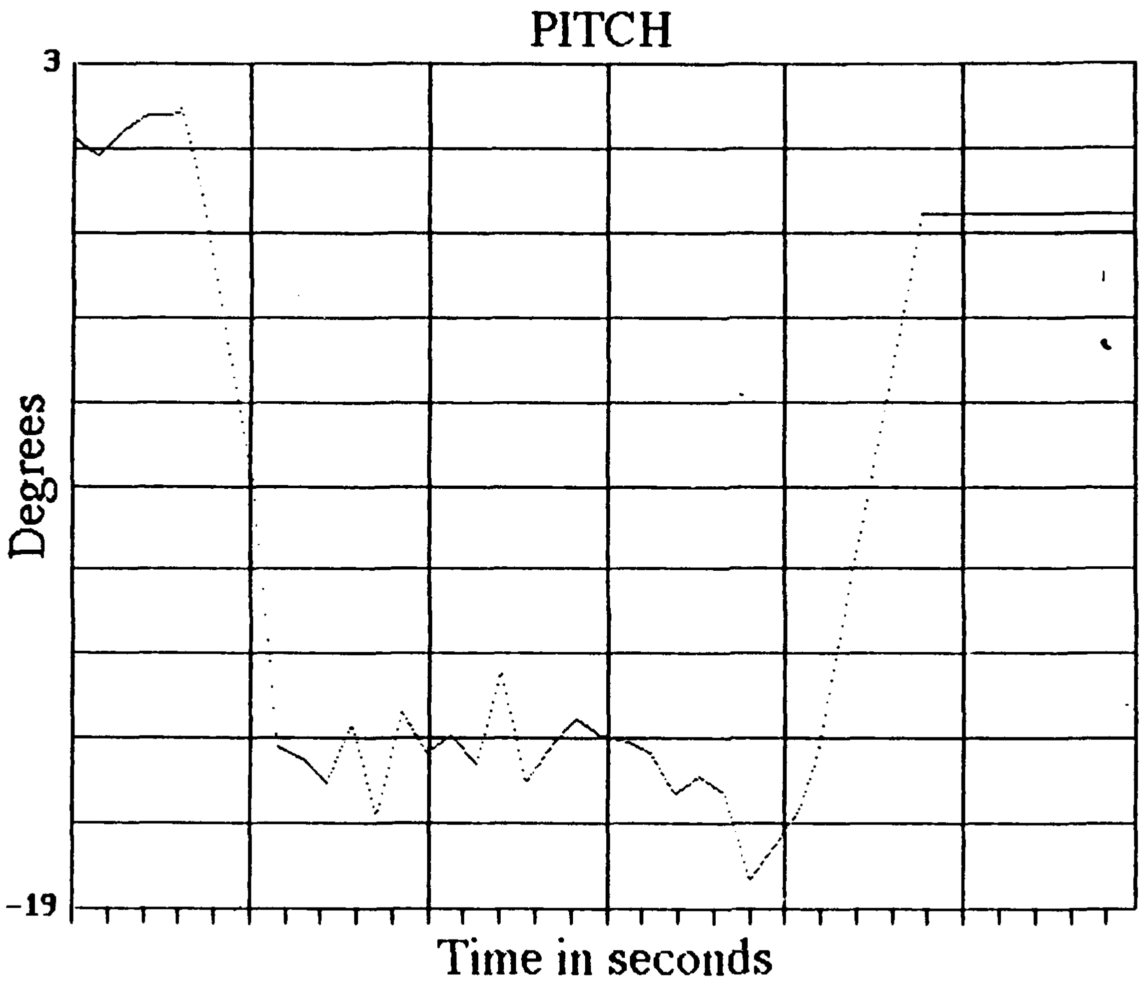
APPENDIX B

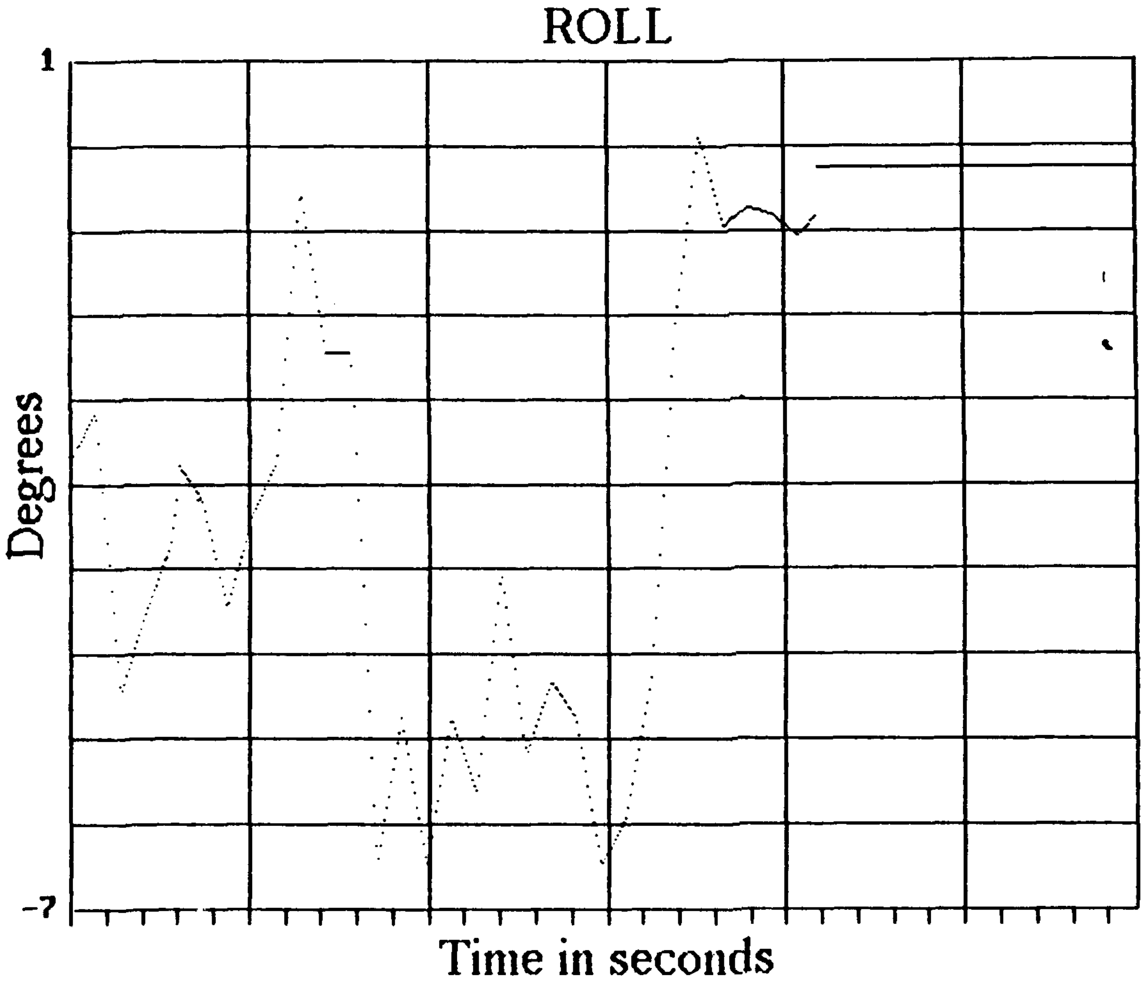
FLIGHT 851/852 TIME HISTORY PLOTS

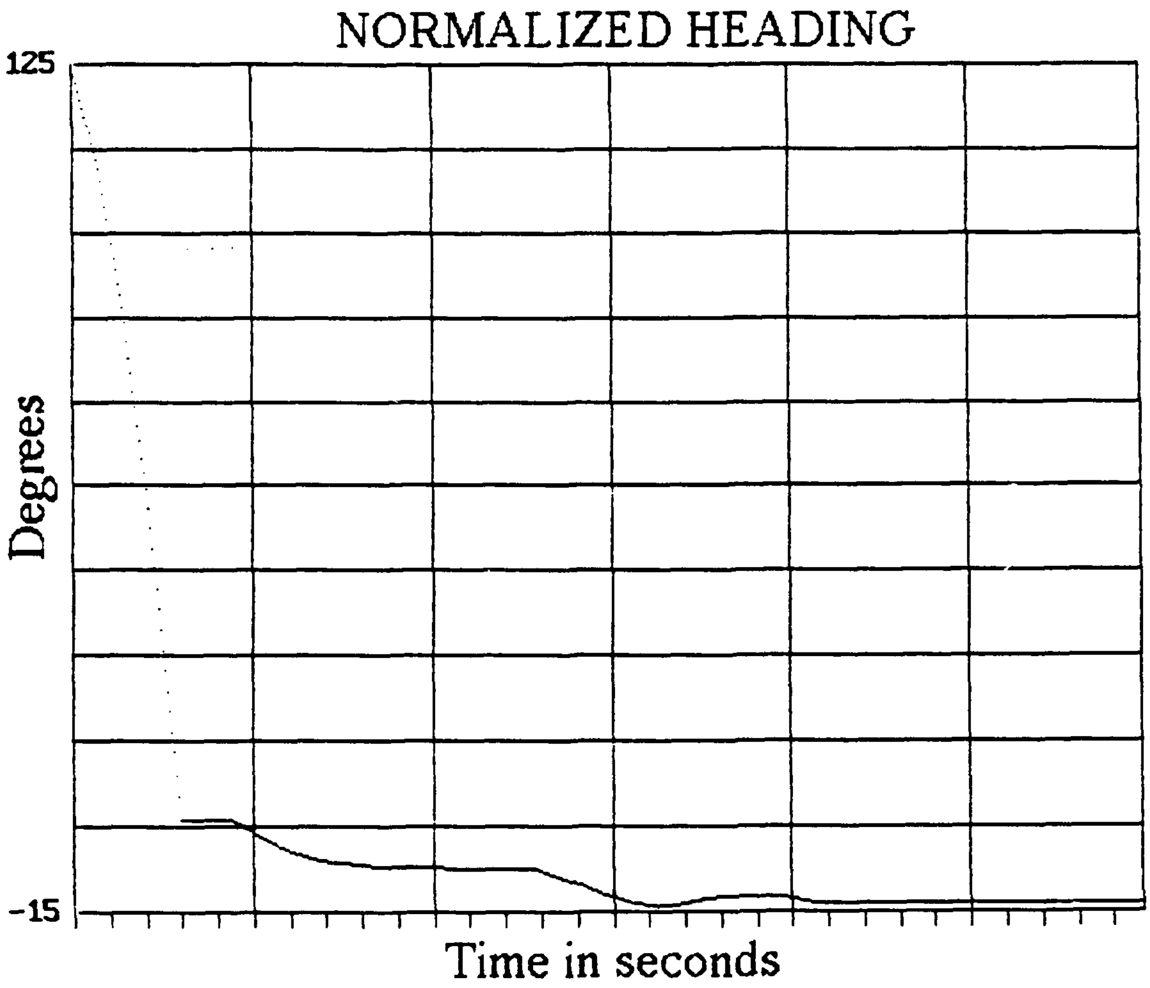


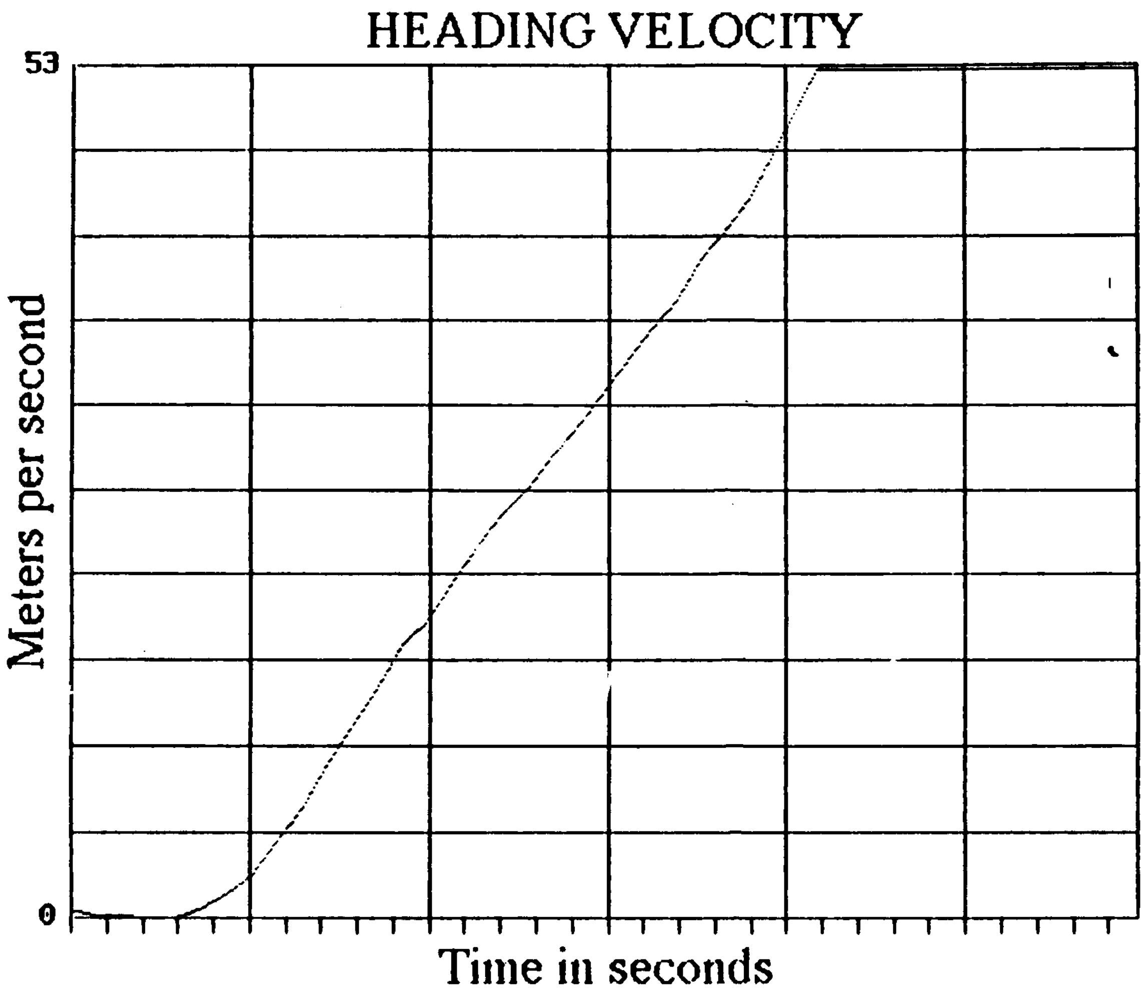

NORMALIZED Y POSITION
878
-1
Meters
Time in seconds

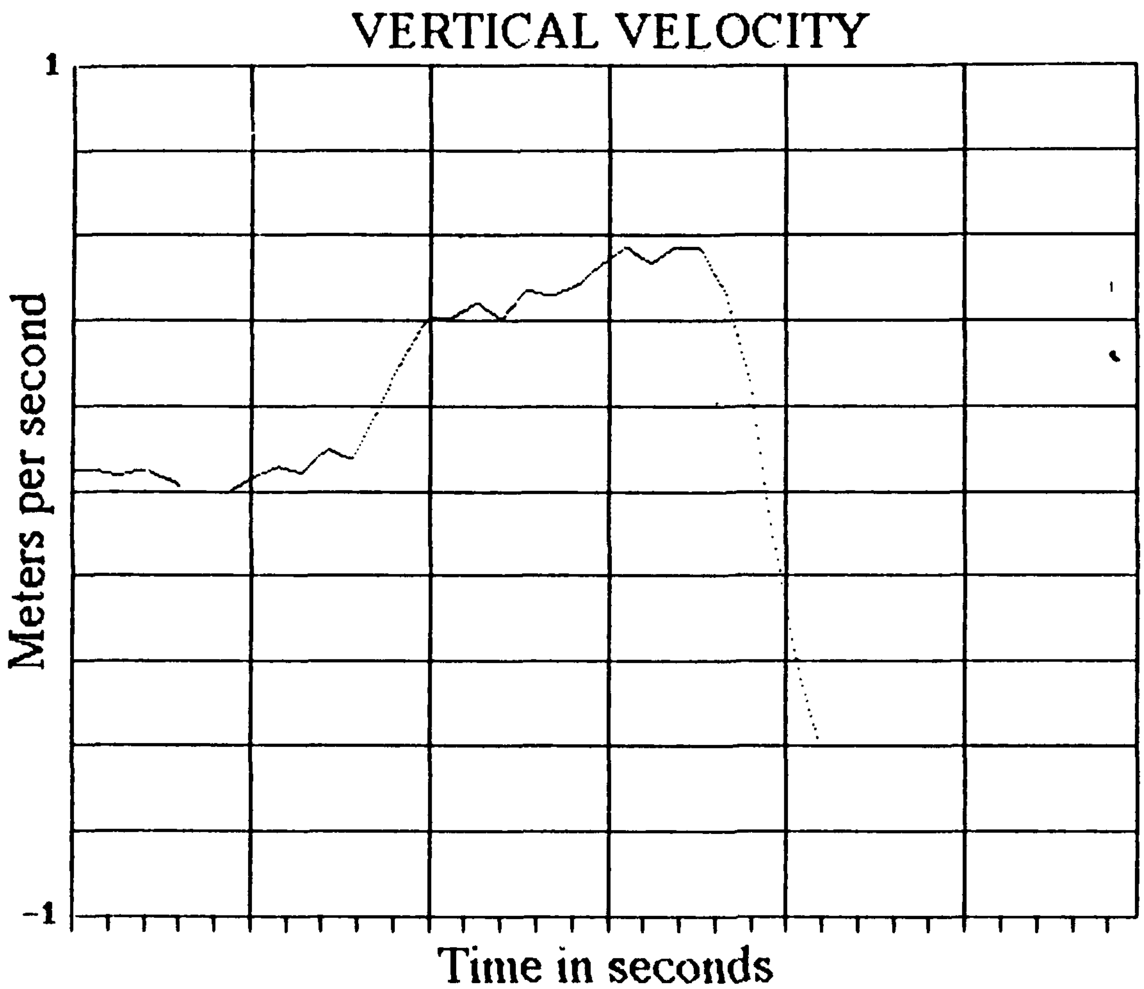

NORMALIZED ALTITUDE
6
0
Meters
Time in seconds

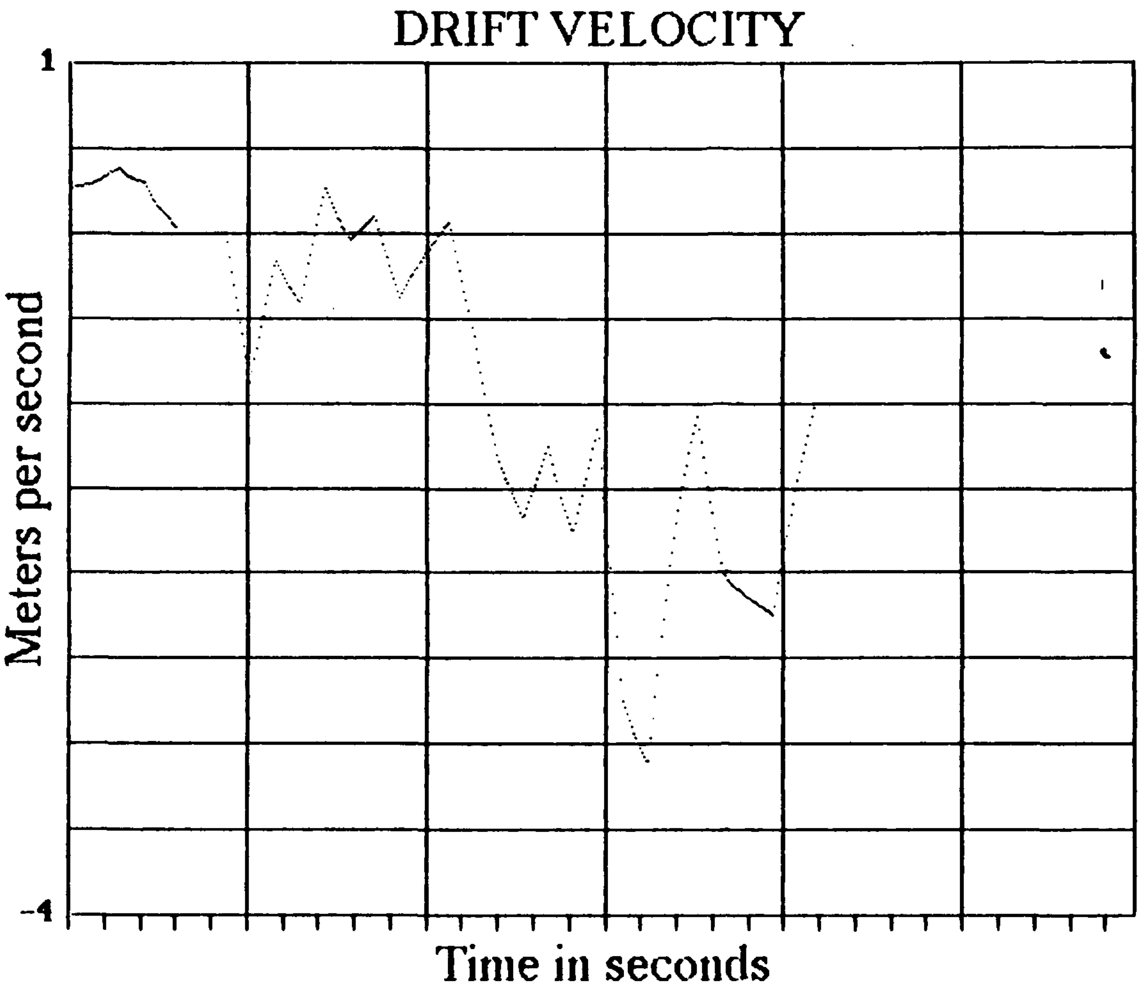

PITCH
3
Degrees
-19
Time in seconds


ROLL
1
-7
Degrees
Time in seconds


NORMALIZED HEADING
125
-15
Degrees
Time in seconds


HEADING VELOCITY
53
0
Meters per second
Time in seconds


VERTICAL VELOCITY
1
-1
Meters per second
Time in seconds

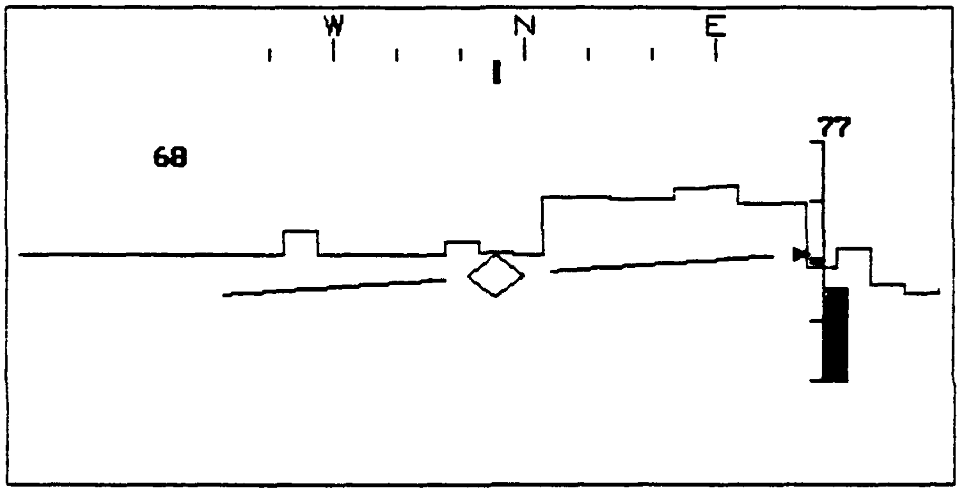

DRIFT VELOCITY
1
-4
Meters per second
Time in seconds

APPENDIX C

SELECTED WOS DISPLAYS AND RADAR PLOTS FOR FLIGHT 851/852

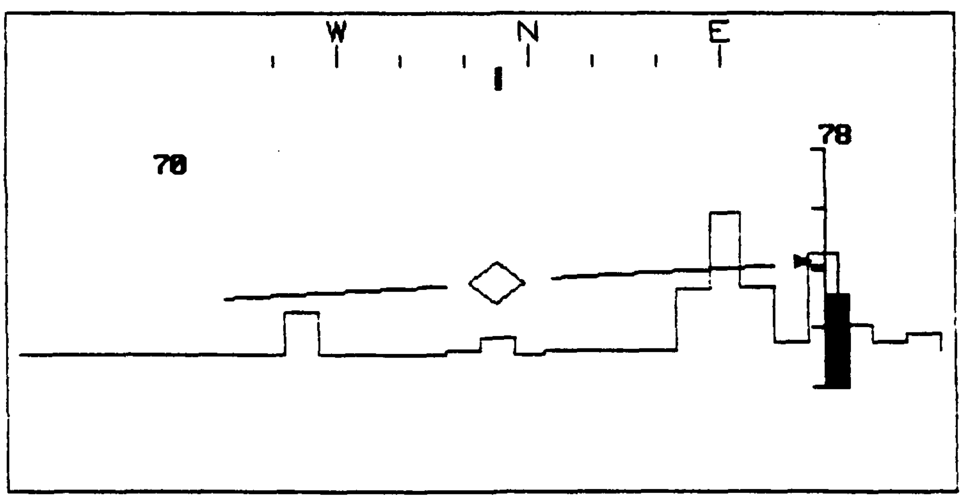
11 9

FLIGHT 851



BES Engineering Services

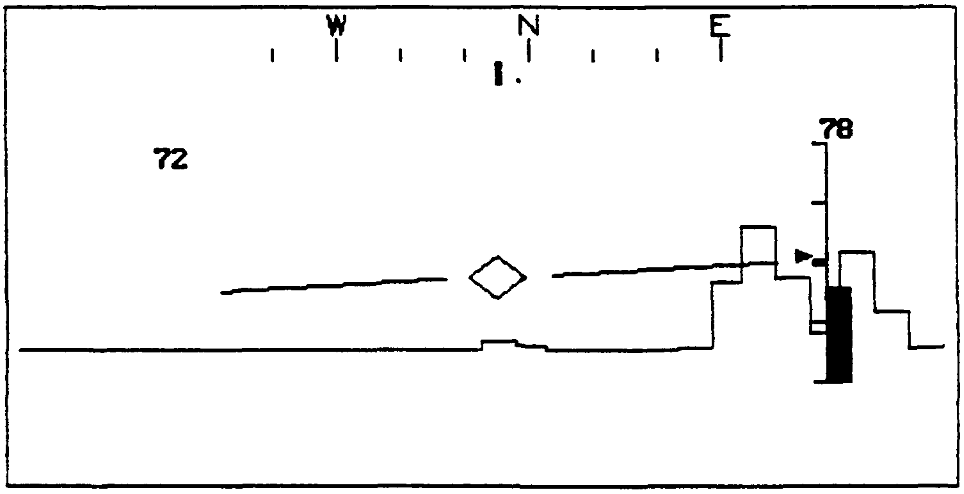
11 14



BES Engineering Services

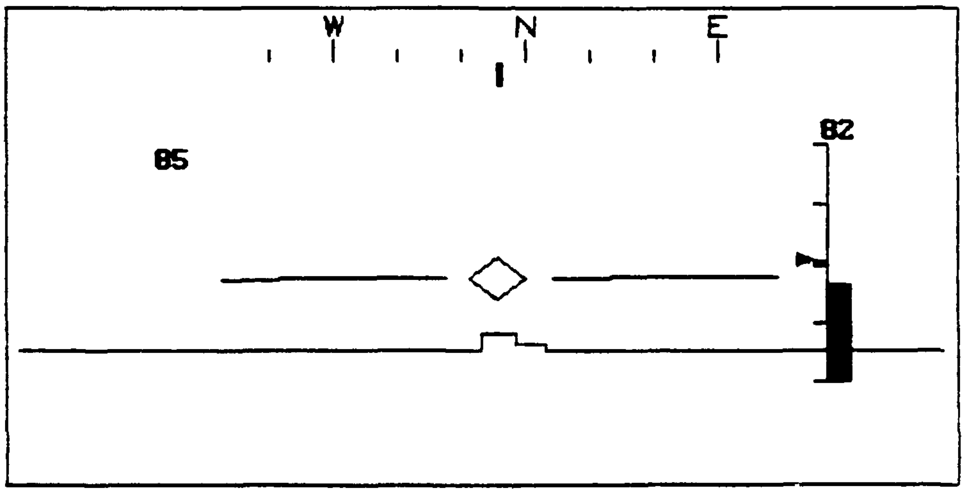
11 18

FLIGHT 851



BES Engineering Services

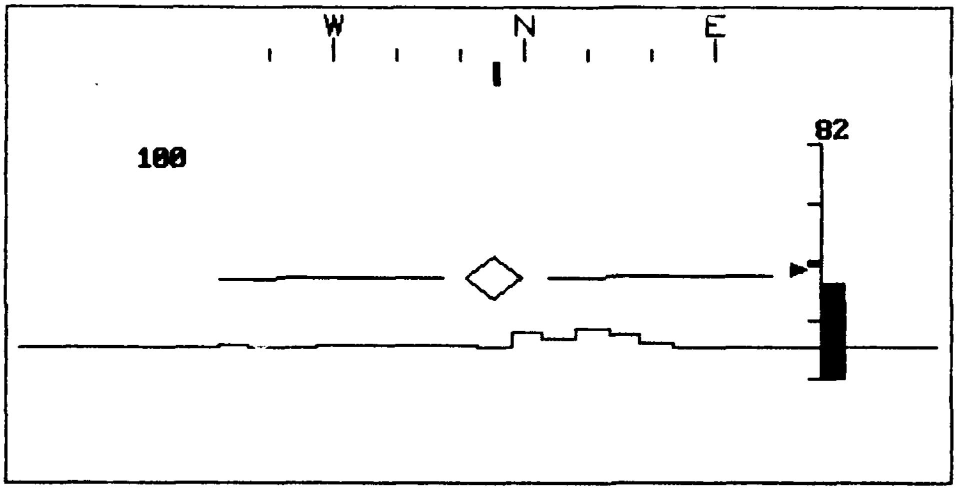
13 8



BES Engineering Services

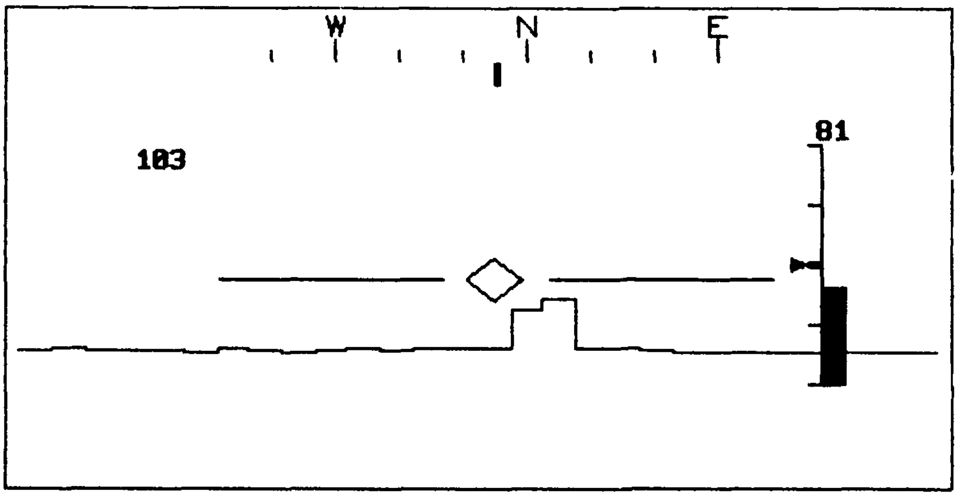
14 15

FLIGHT 851



BES Engineering Services

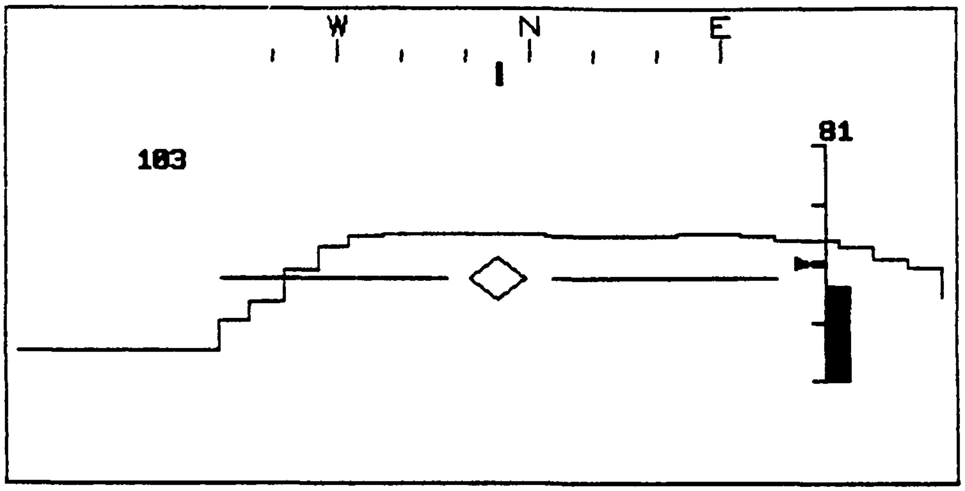
15 6



BES Engineering Services

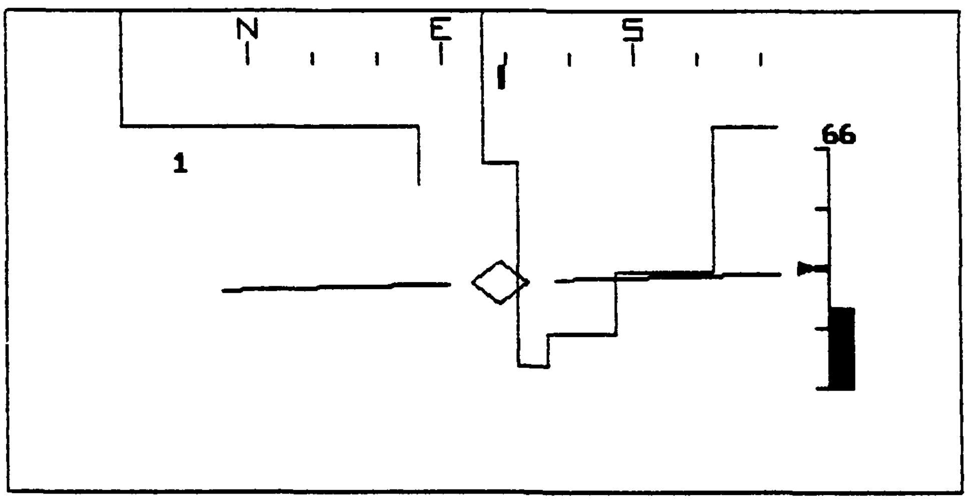
17 7

FLIGHT 851



BES Engineering Services

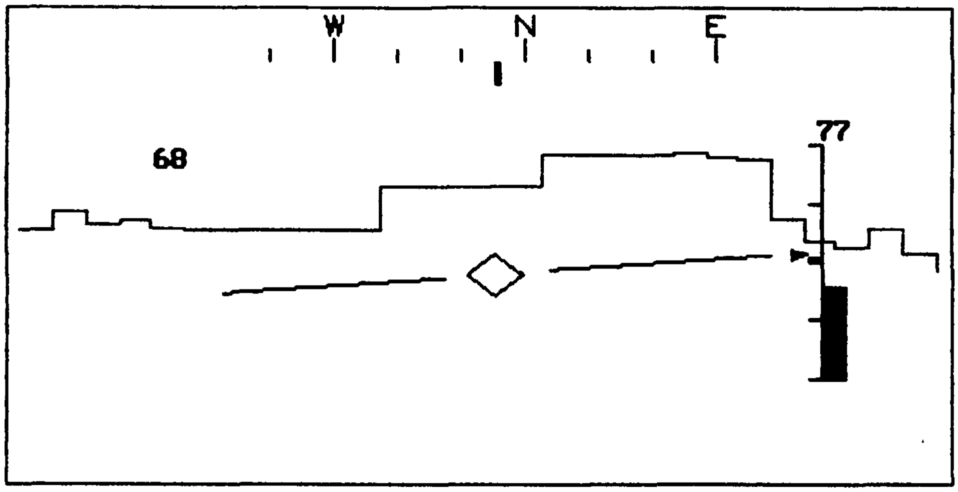
1 4



BES Engineering Services

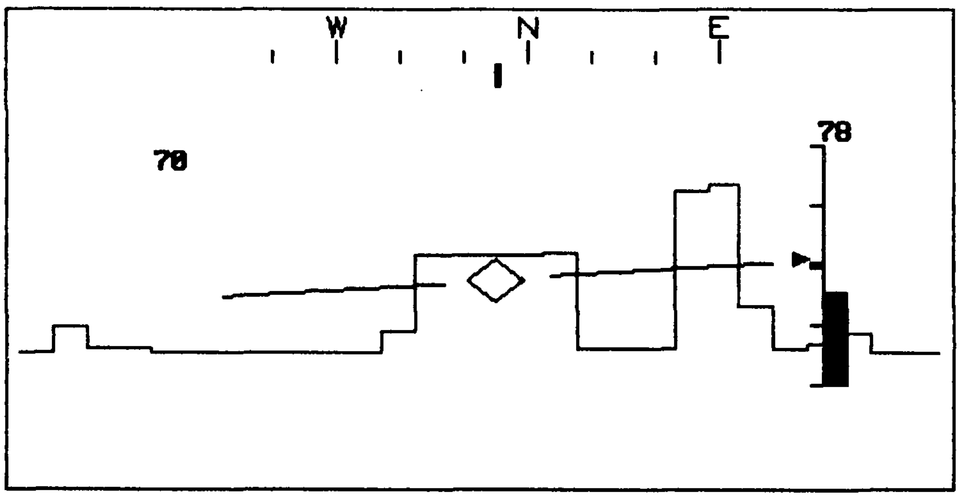
9

FLIGHT 852



BES Engineering Services

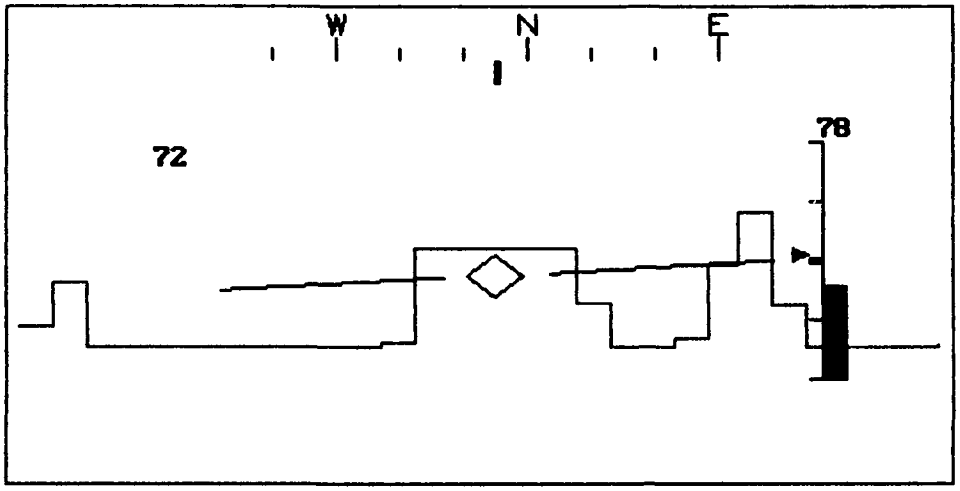
14



BES Engineering Services

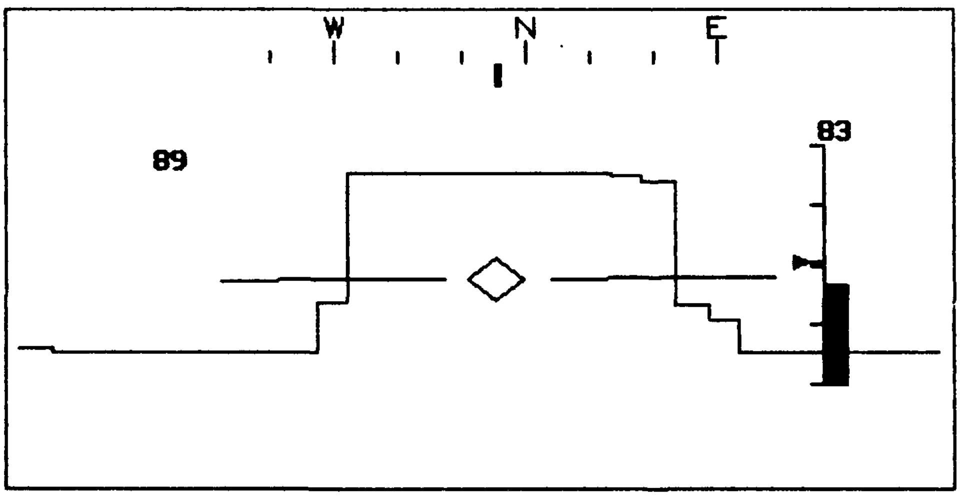
18

FLIGHT 852



BES Engineering Services

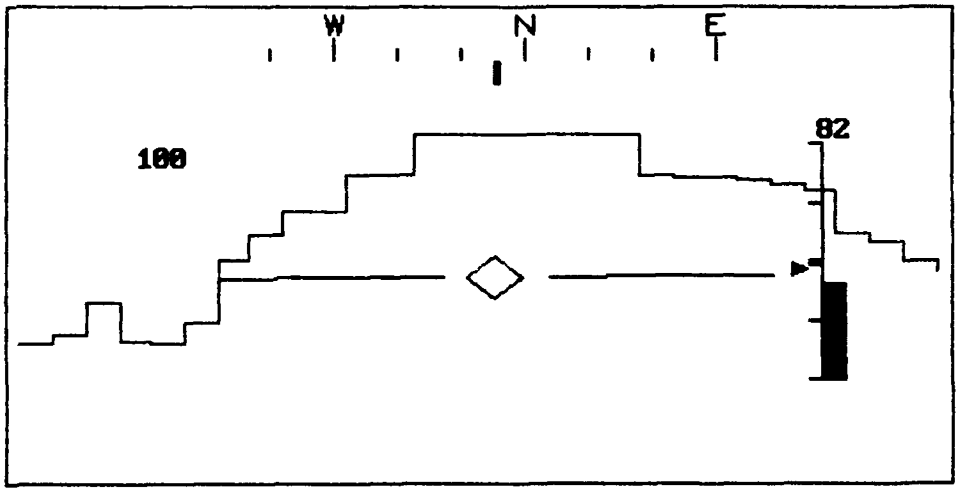
18



BES Engineering Services

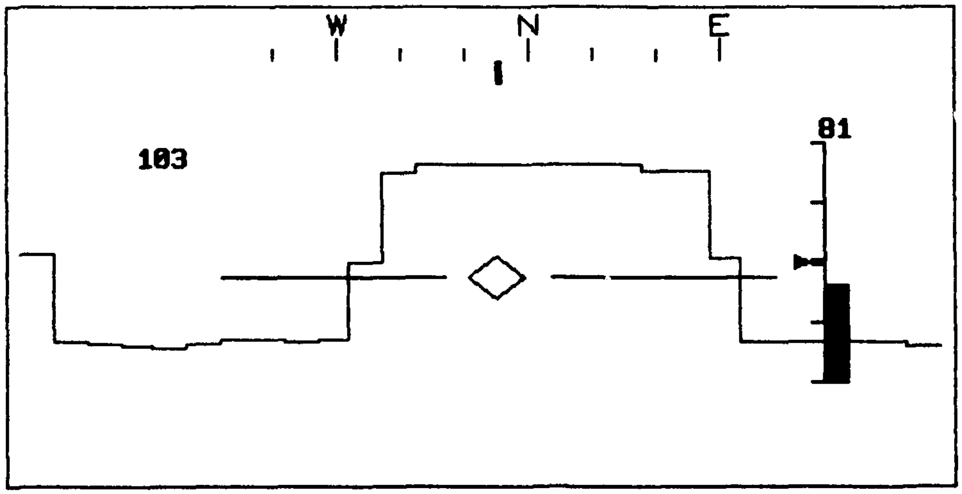
15

FLIGHT 852



BES Engineering Services

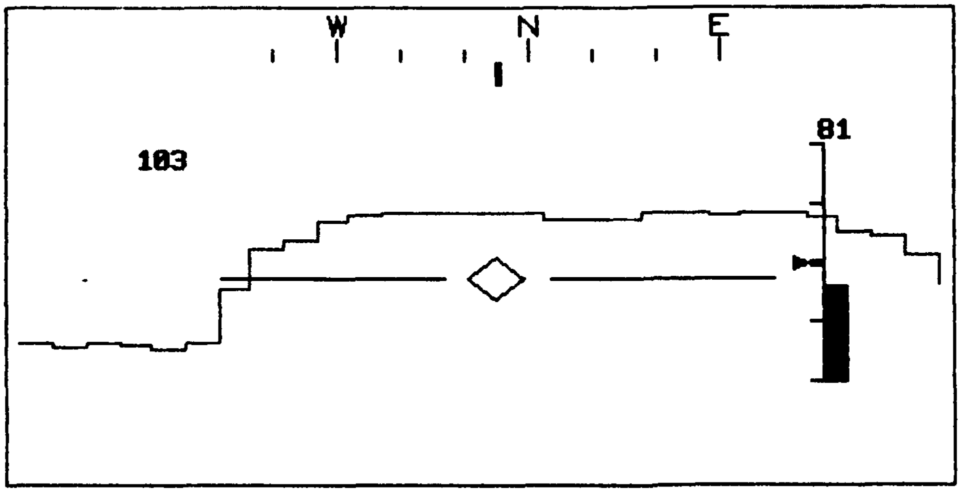
6



BES Engineering Services

7

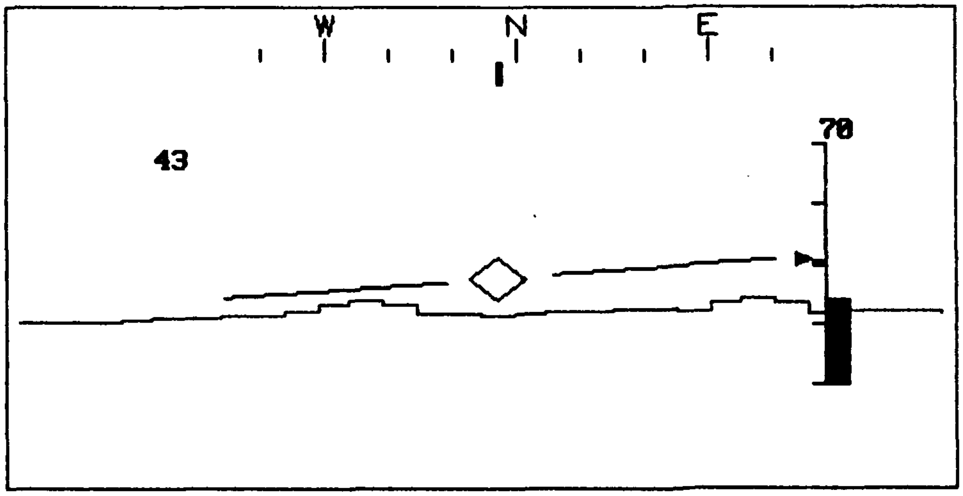
FLIGHT 852



BES Engineering Services

9

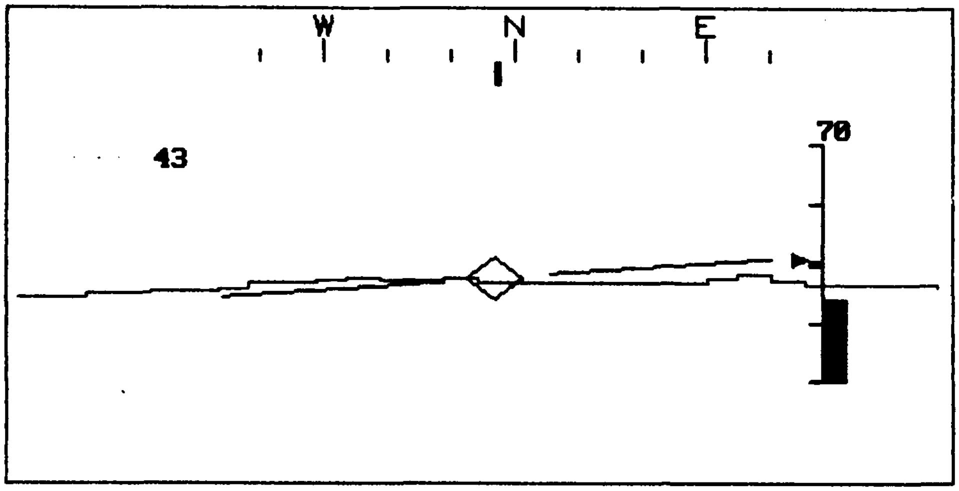
FLIGHT 851



BES Engineering Services

9

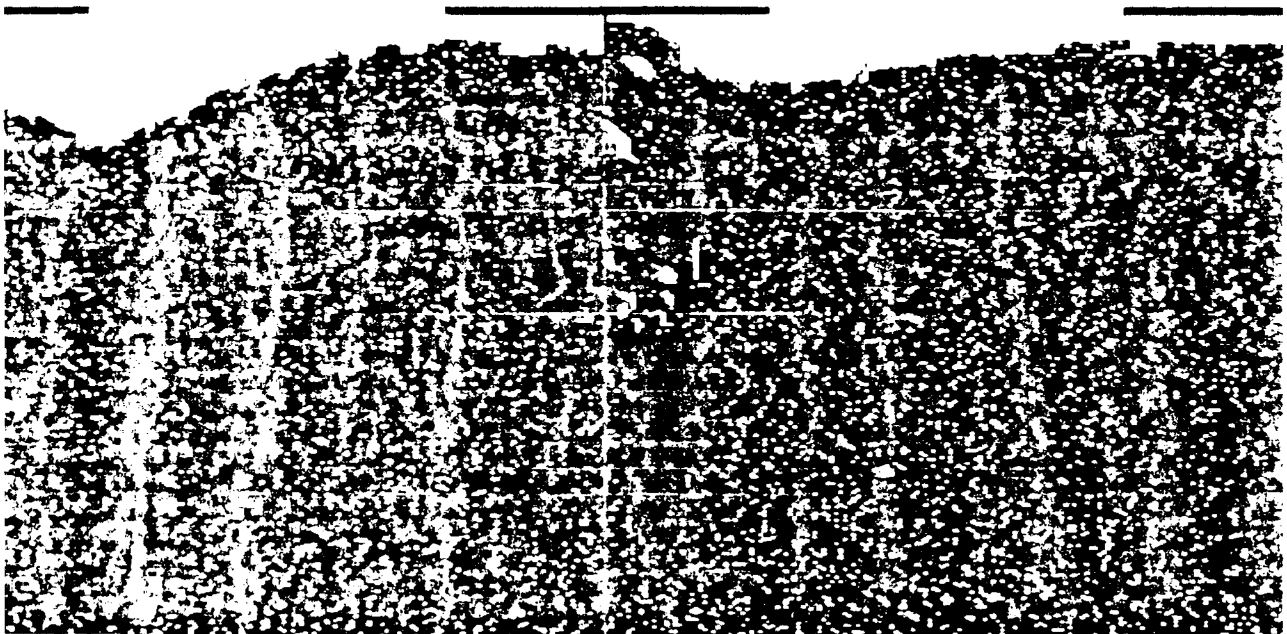
FLIGHT 852



BES Engineering Services

essed Radar Data Frame 8
Time to process half frame 385 milliseconds

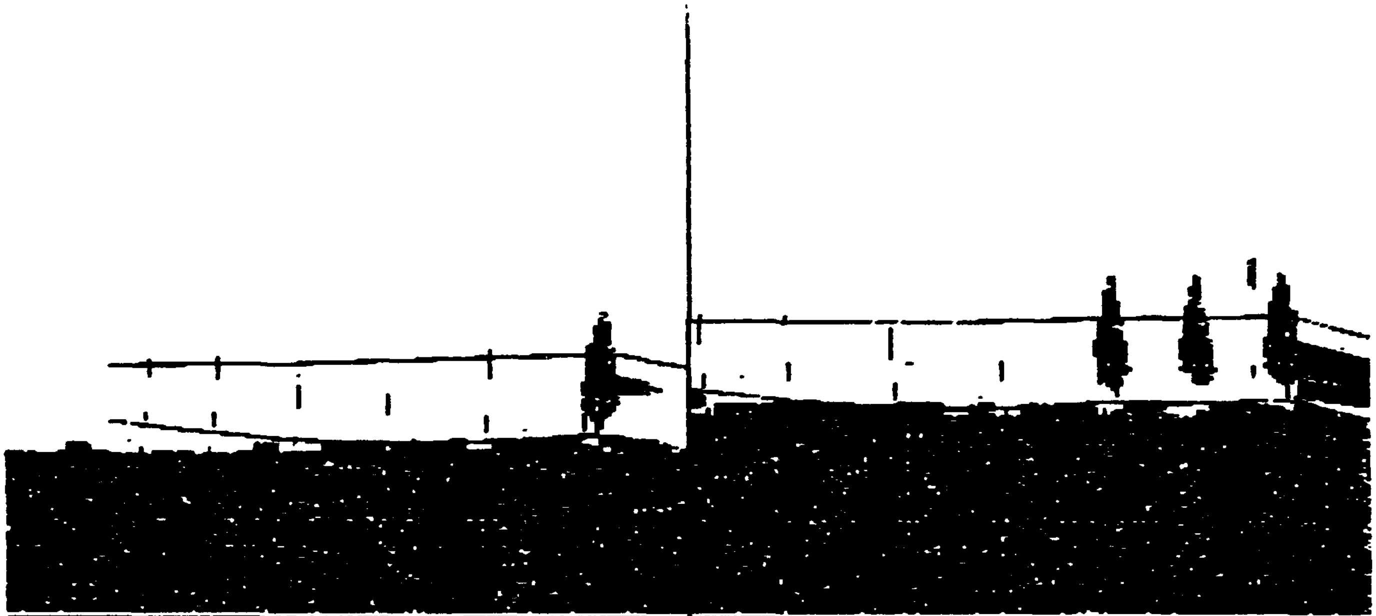
RADAR SIMULATION



essed Radar Data Frame 11
Time to process half frame 290 milliseconds

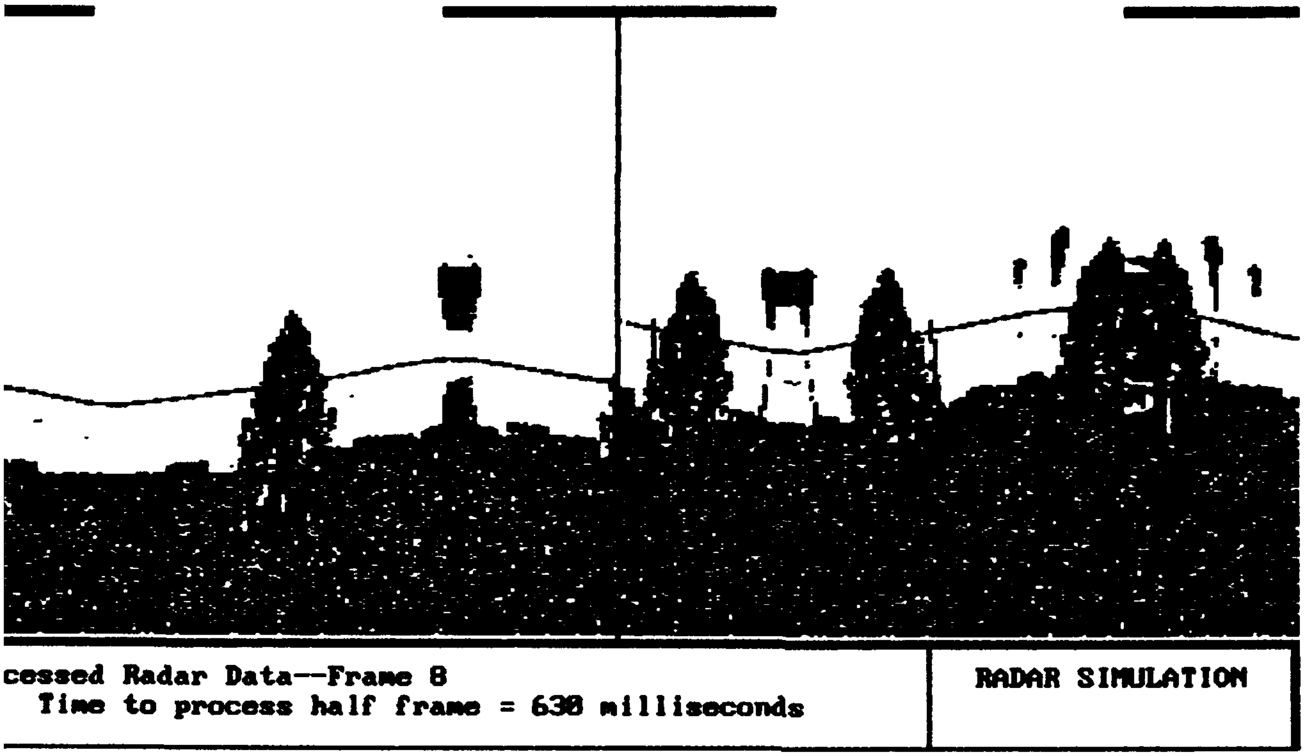
RADAR SIMULATION

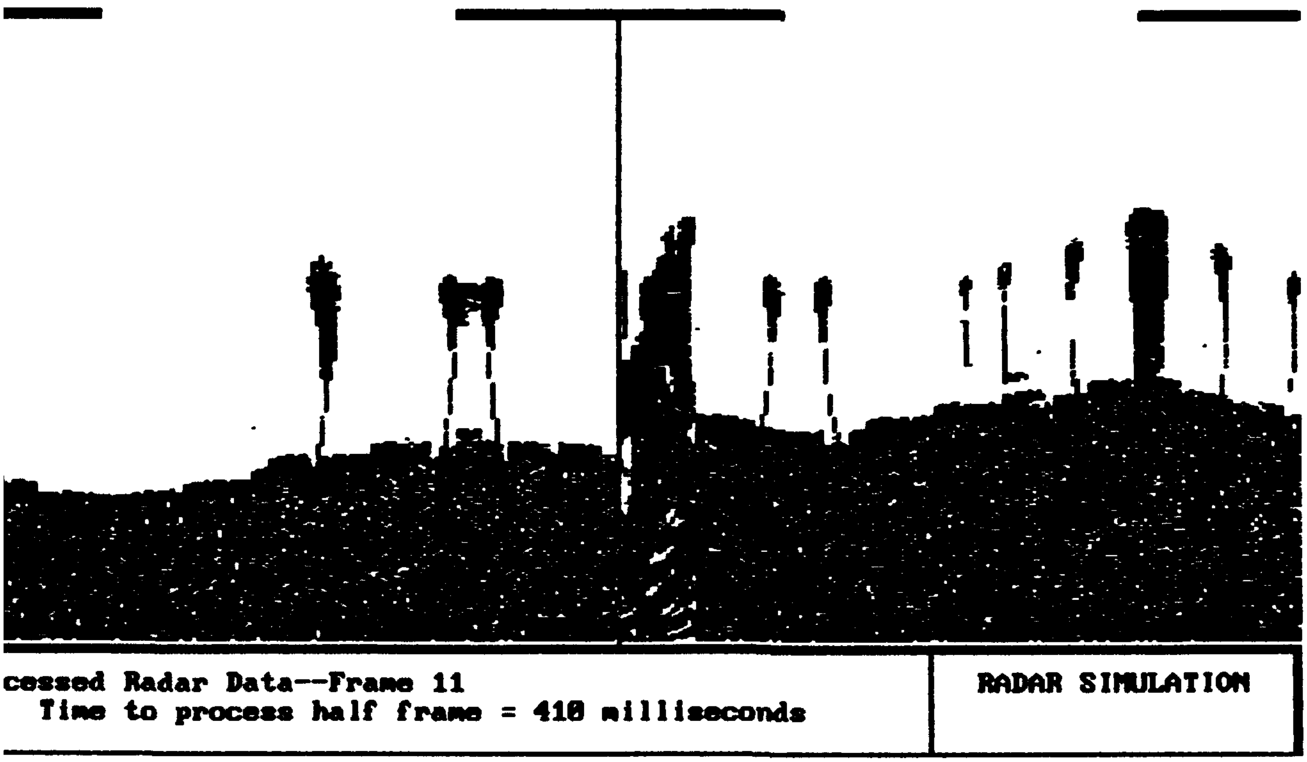
FLIGHT 851



Processed Radar Data--Frame 2 Time to process half frame = 410 milliseconds	RADAR SIMULATION

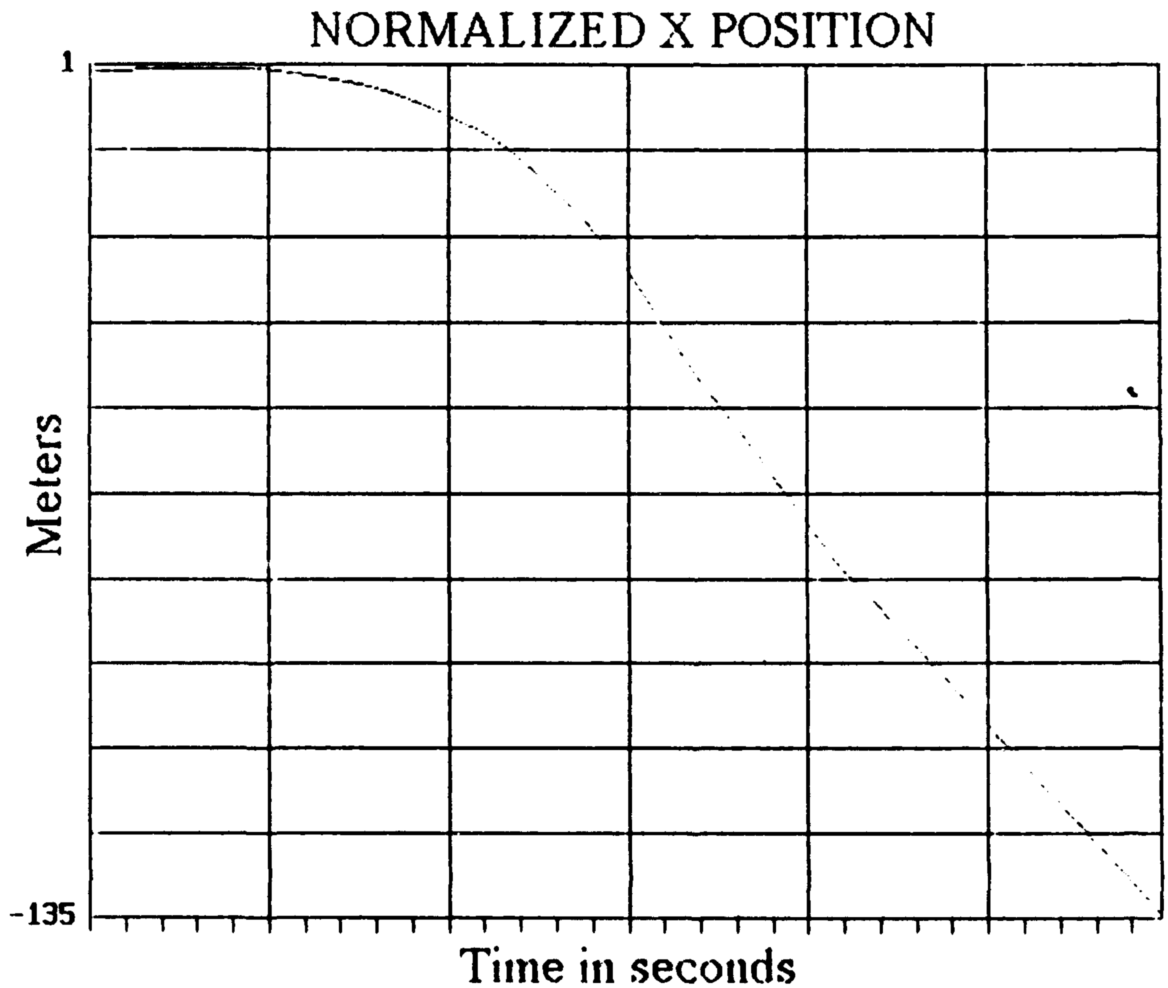
FLIGHT 852

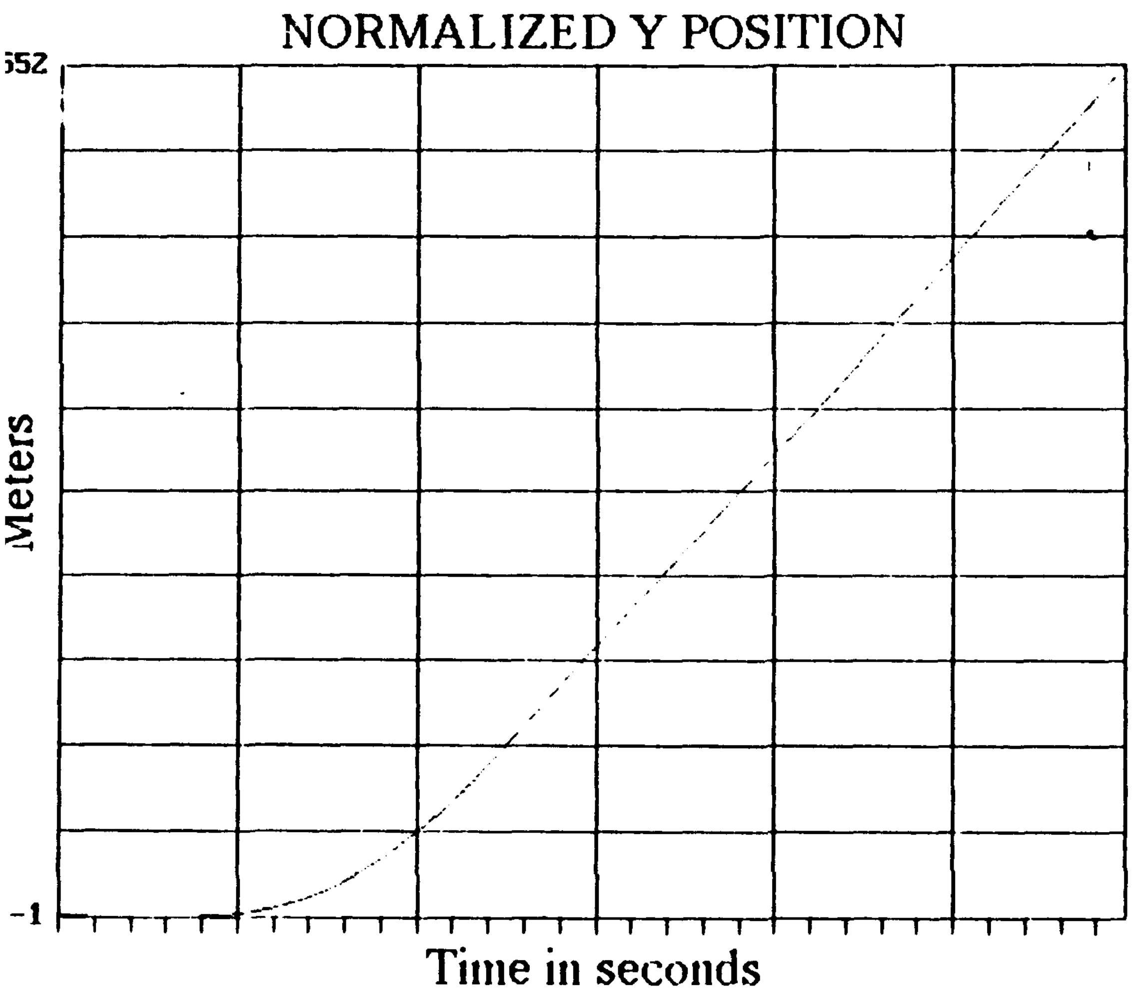

cessed Radar Data--Frame 8
Time to process half frame = 630 milliseconds
RADAR SIMULATION

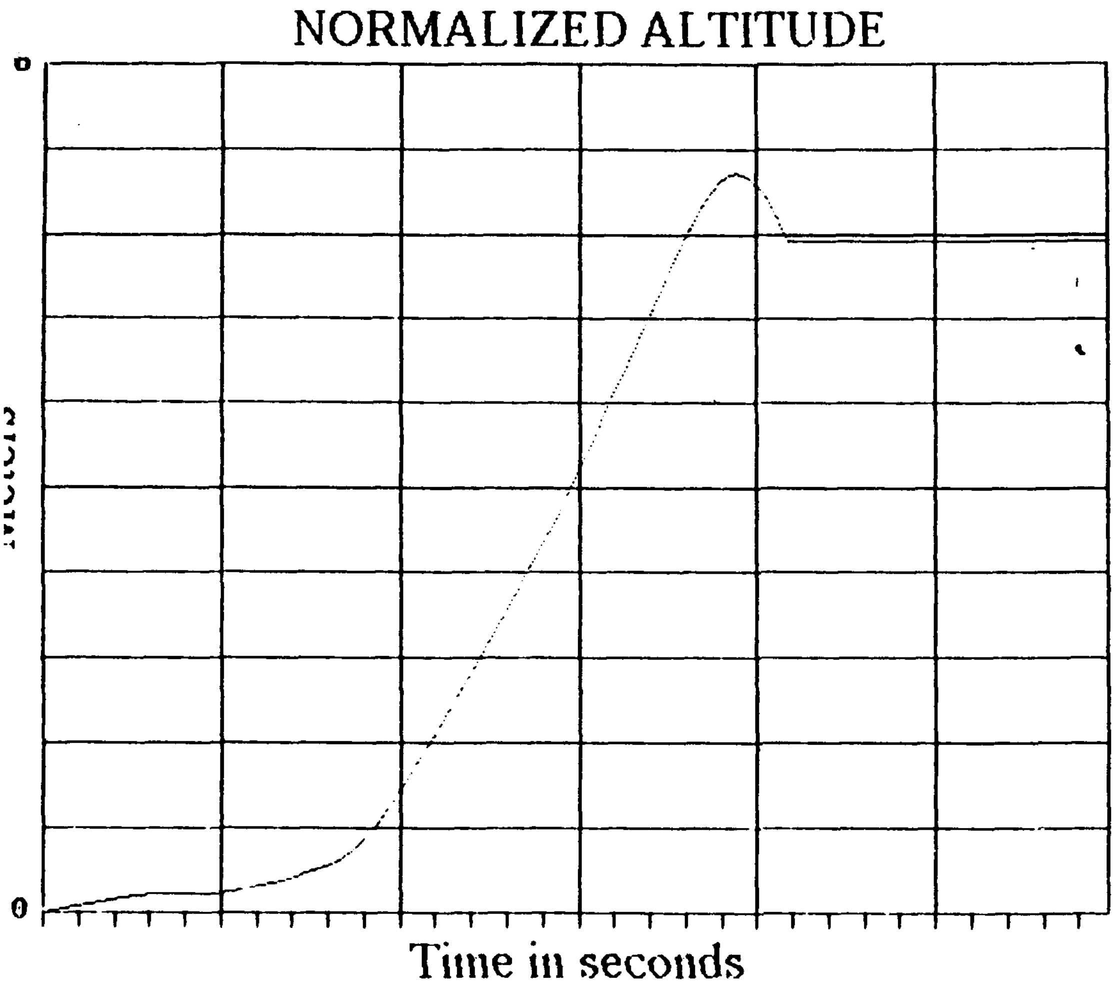

cessed Radar Data--Frame 11
Time to process half frame = 410 milliseconds
RADAR SIMULATION

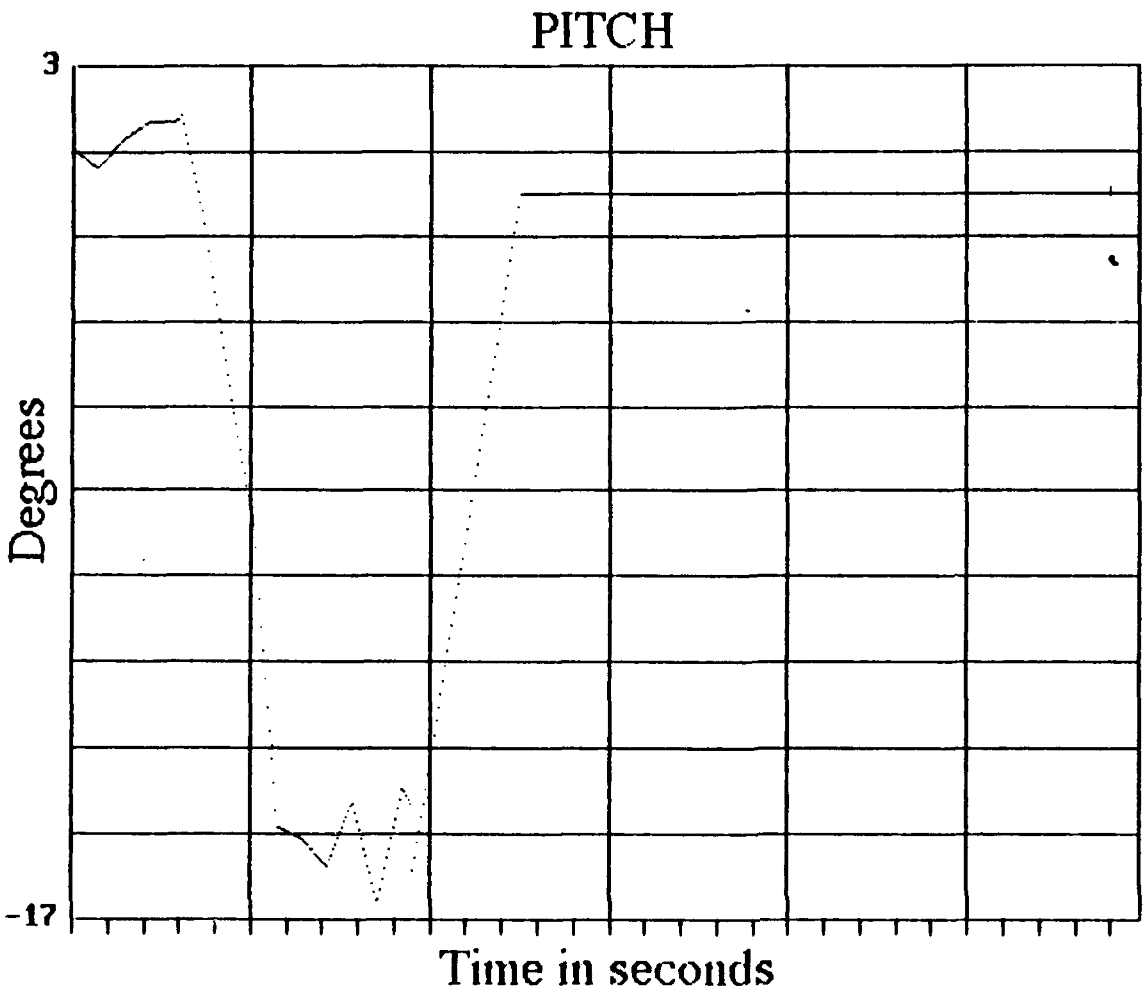
APPENDIX D

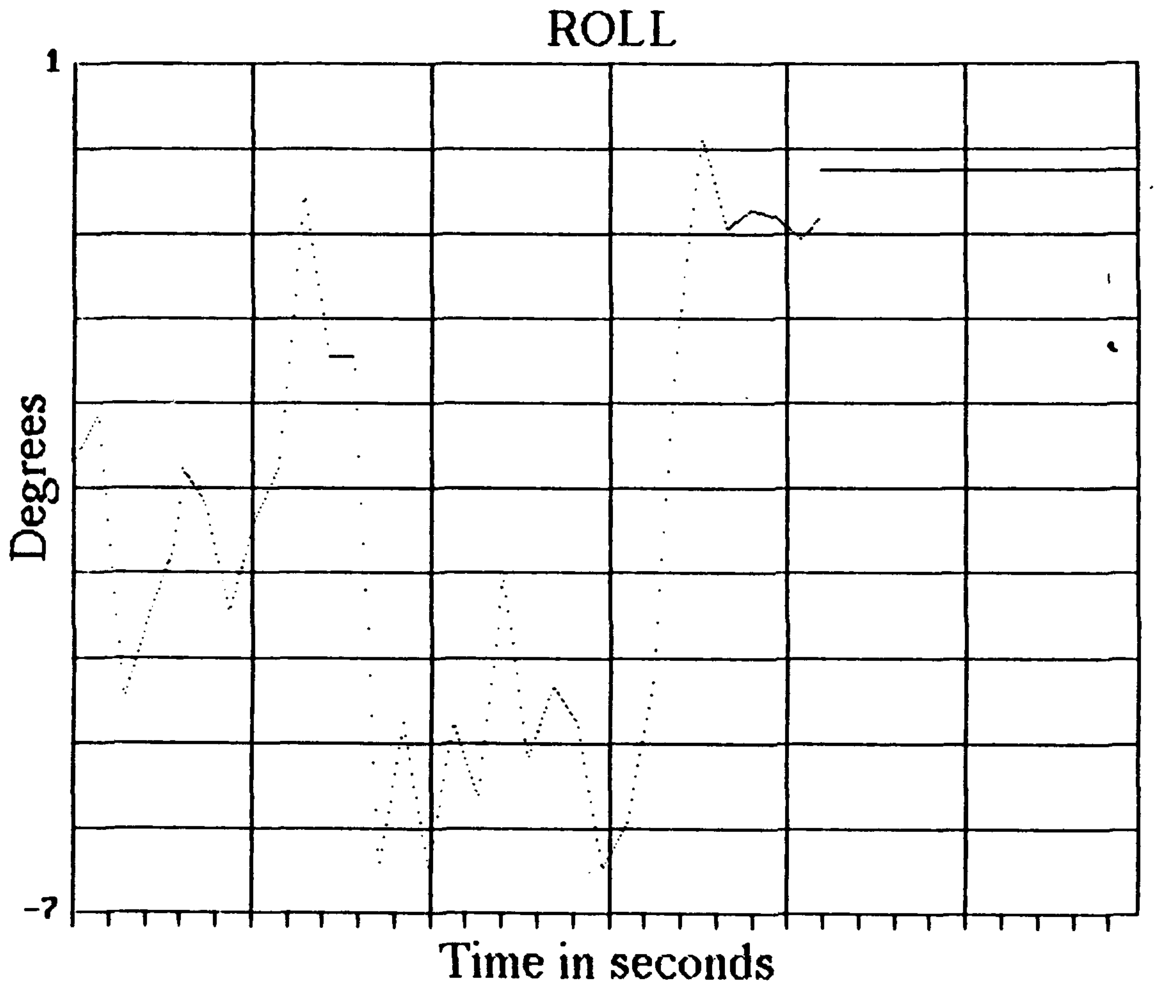
FLIGHT 853/861 TIME HISTORY PLOTS

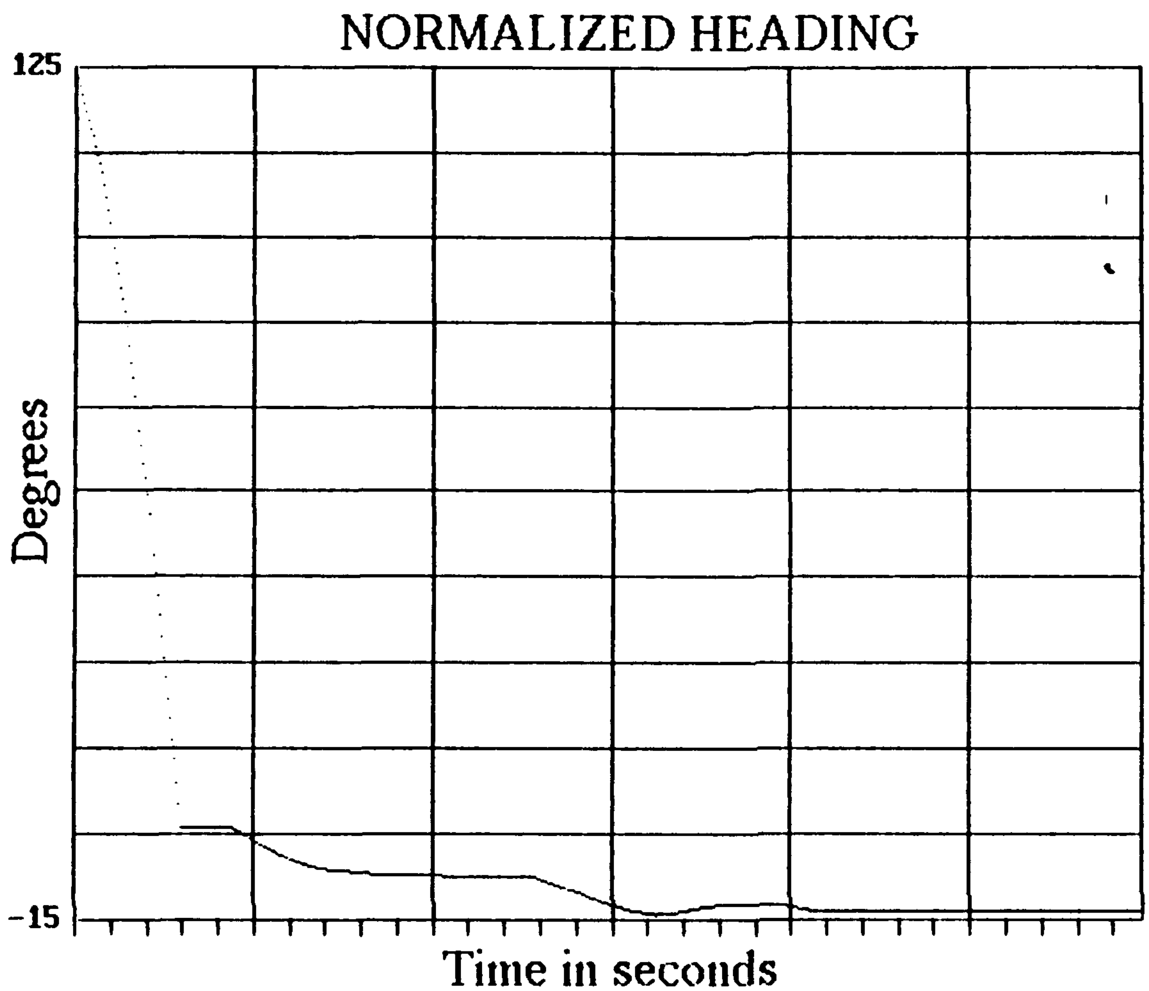


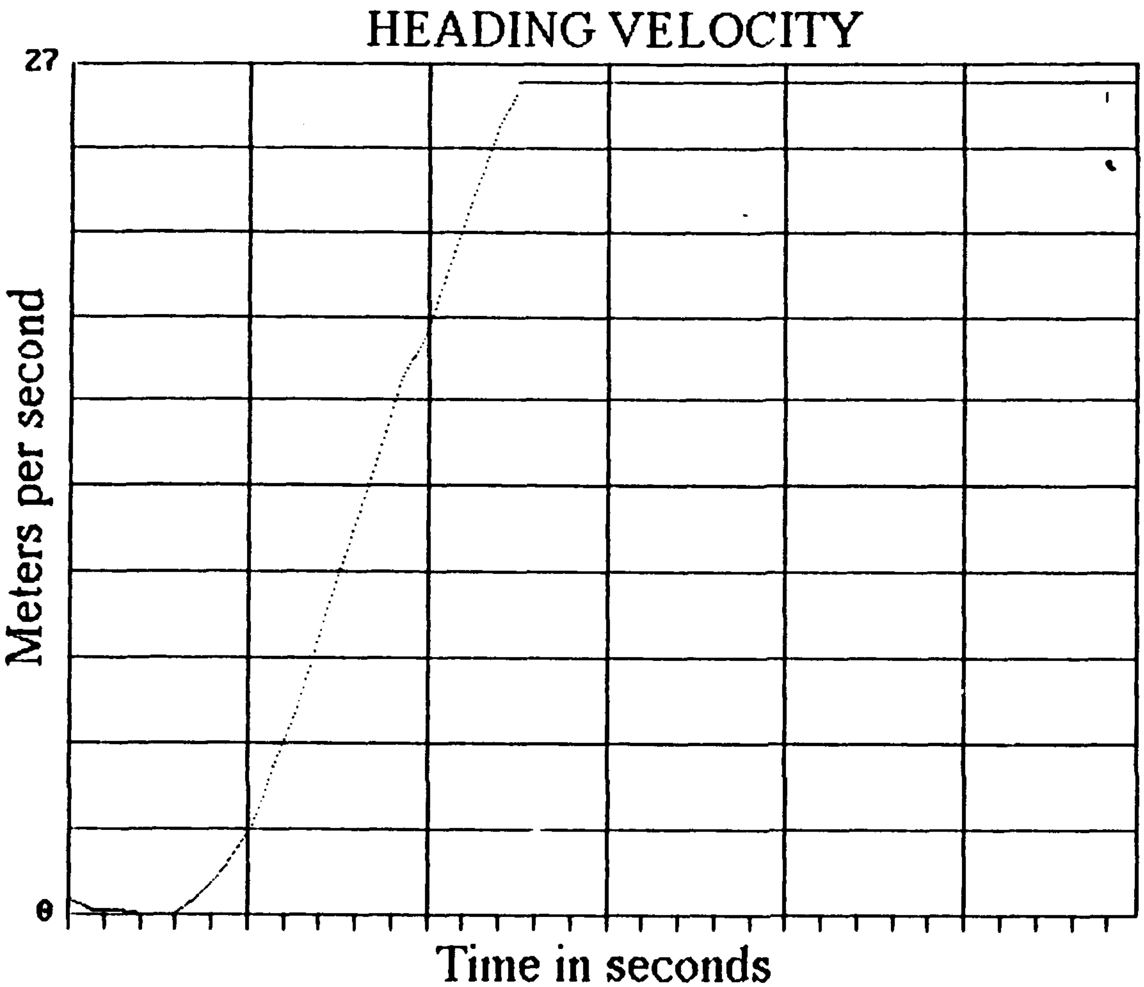

NORMALIZED Y POSITION
552
-1
Meters
Time in seconds

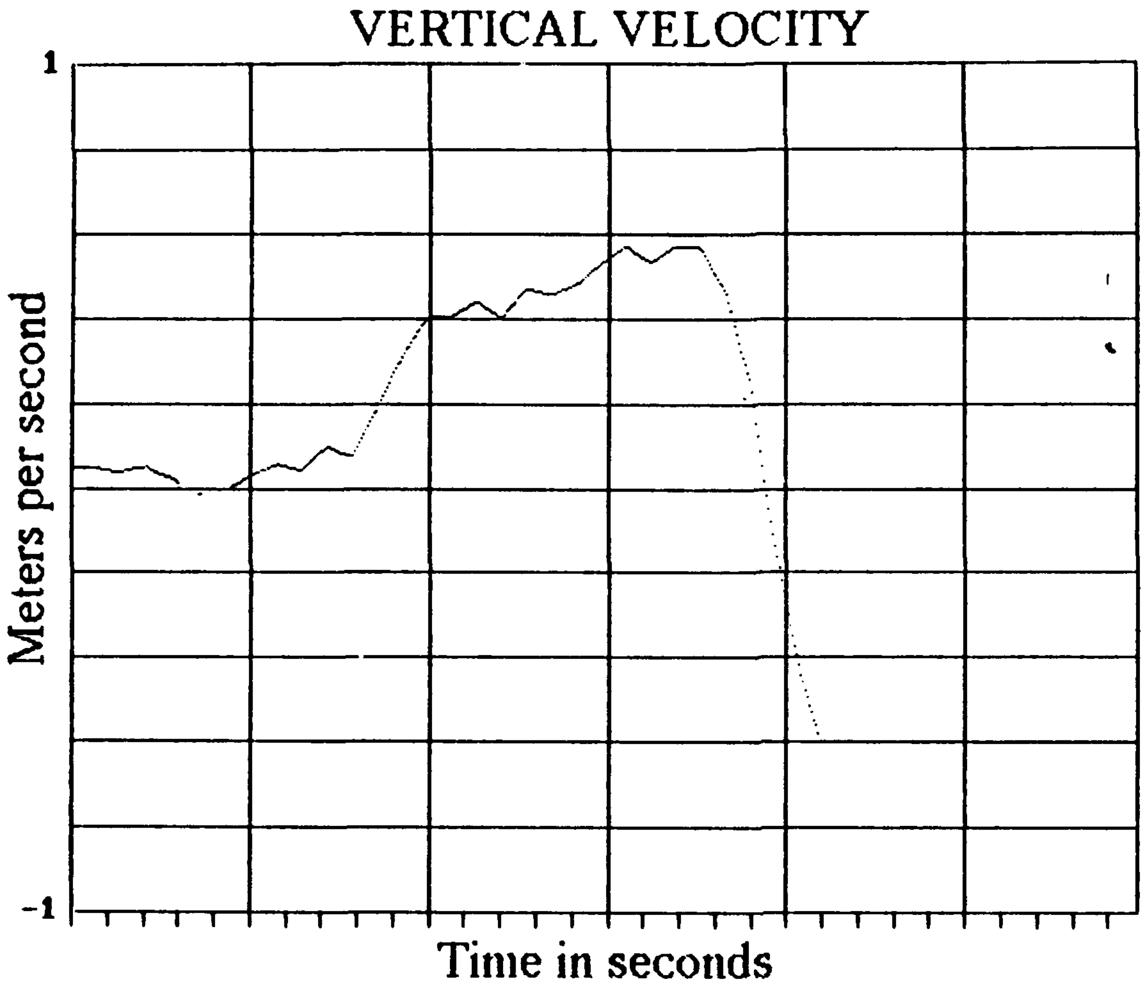

NORMALIZED ALTITUDE
0
0
Time in seconds

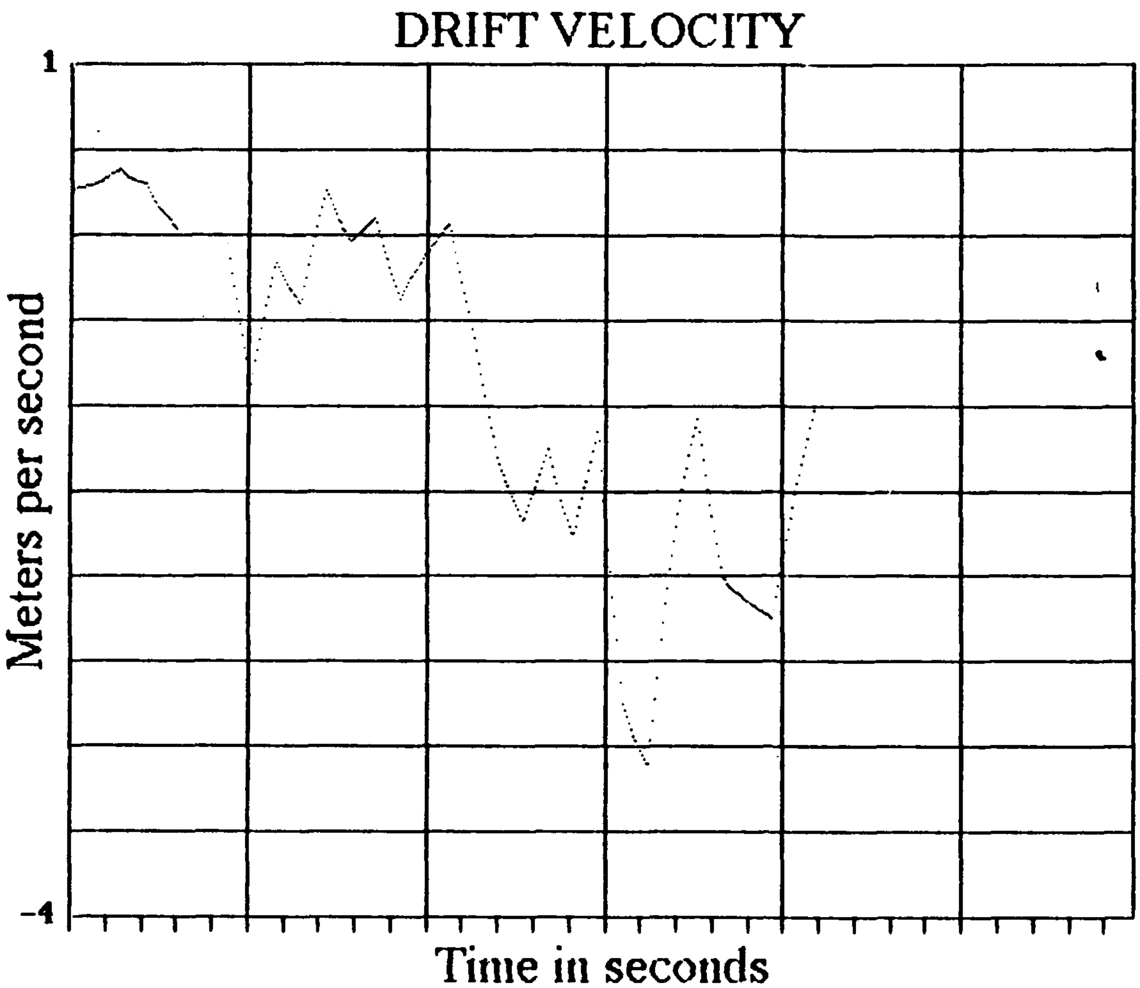

PITCH
3
-17
Degrees
Time in seconds


ROLL
1
-7
Degrees
Time in seconds


NORMALIZED HEADING
125
-15
Degrees
Time in seconds


HEADING VELOCITY
27
0
Meters per second
Time in seconds


VERTICAL VELOCITY
1
-1
Meters per second
Time in seconds

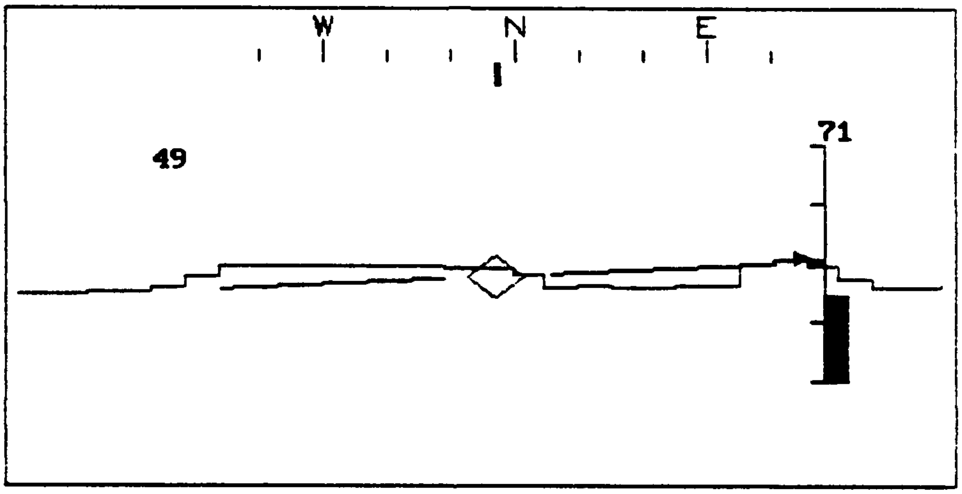

DRIFT VELOCITY
1
-4
Meters per second
Time in seconds

APPENDIX E

SELECTED WOS DISPLAYS AND RADAR PLOTS FOR FLIGHT 853/861

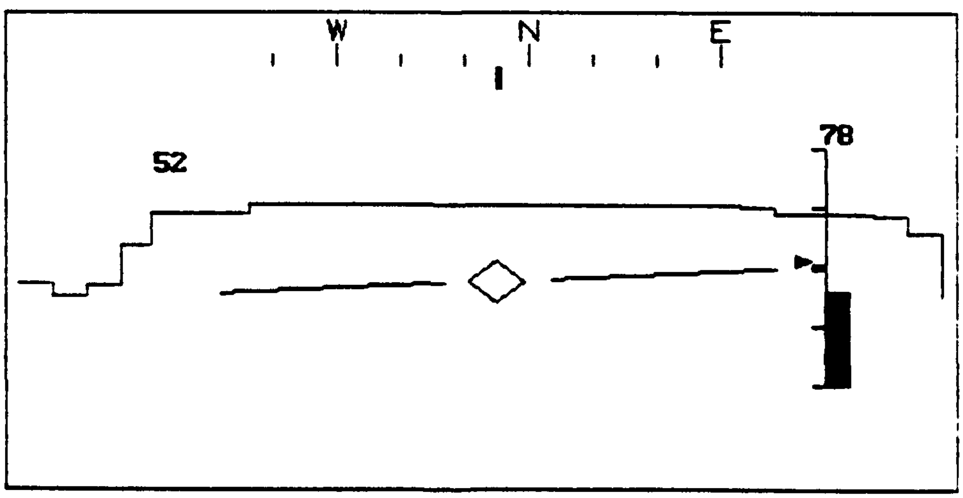
9 2

FLIGHT 853



BES Engineering Services

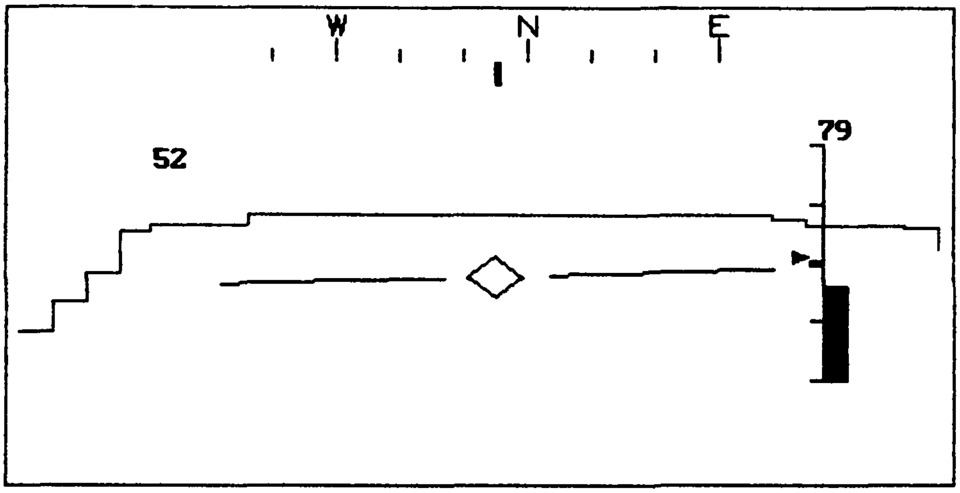
11 20



BES Engineering Services

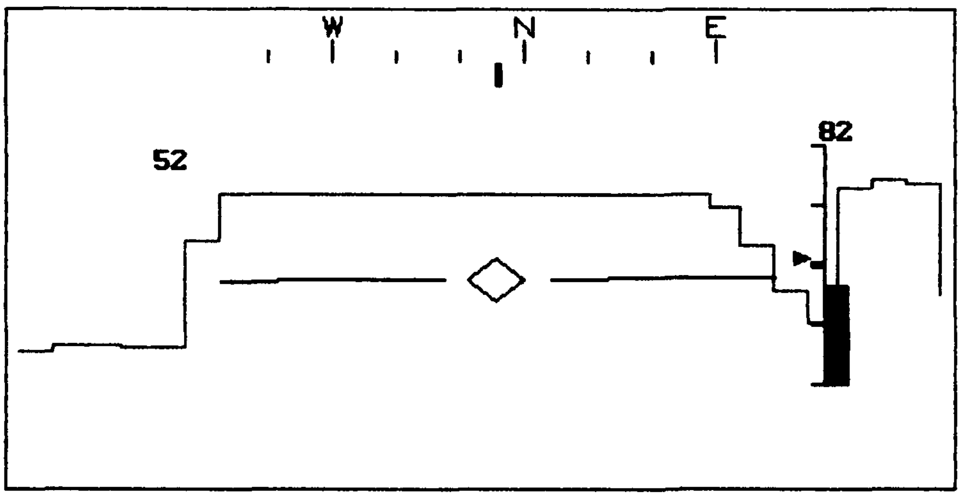
4

FLIGHT 853



BES Engineering Services

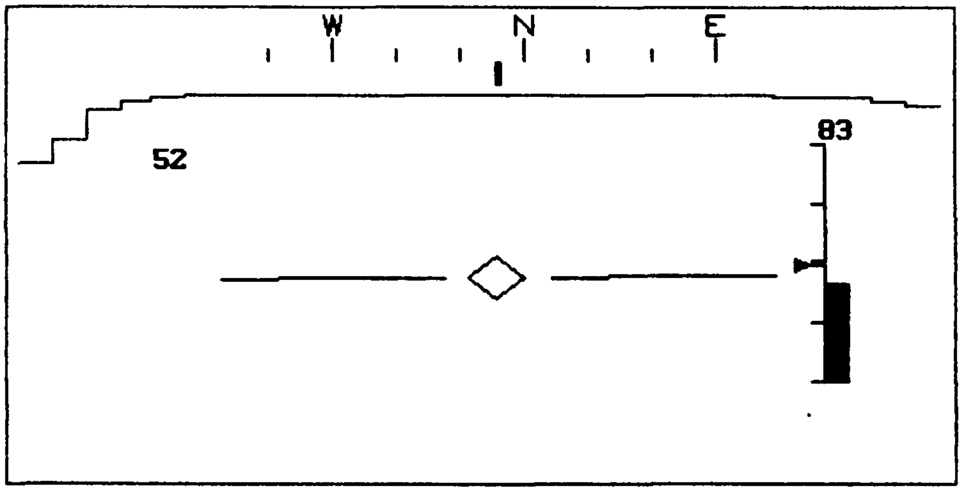
6



BES Engineering Services

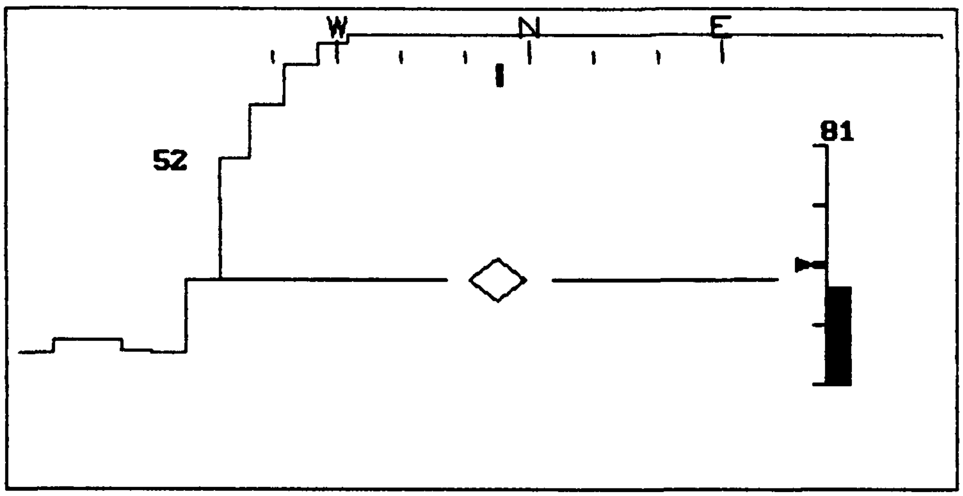
4

FLIGHT 853



BES Engineering Services

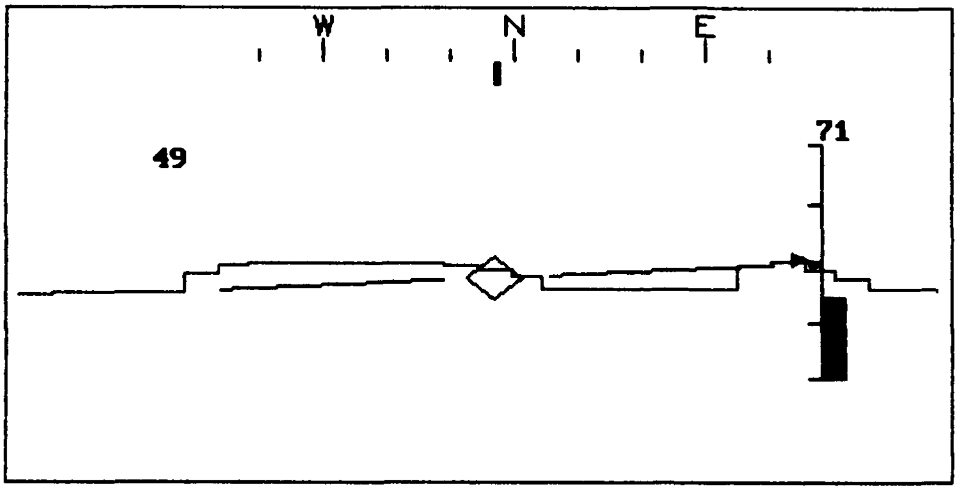
6



BES Engineering Services

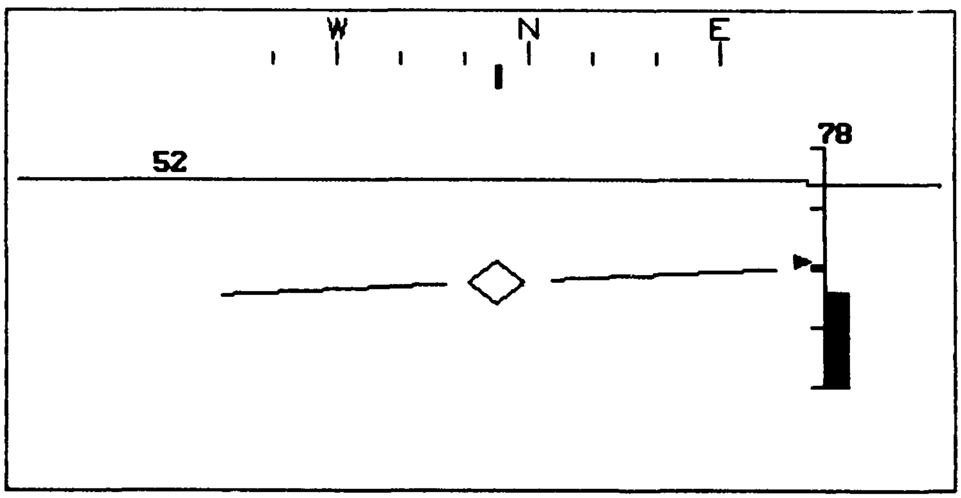
2

FLIGHT 861



BES Engineering Services

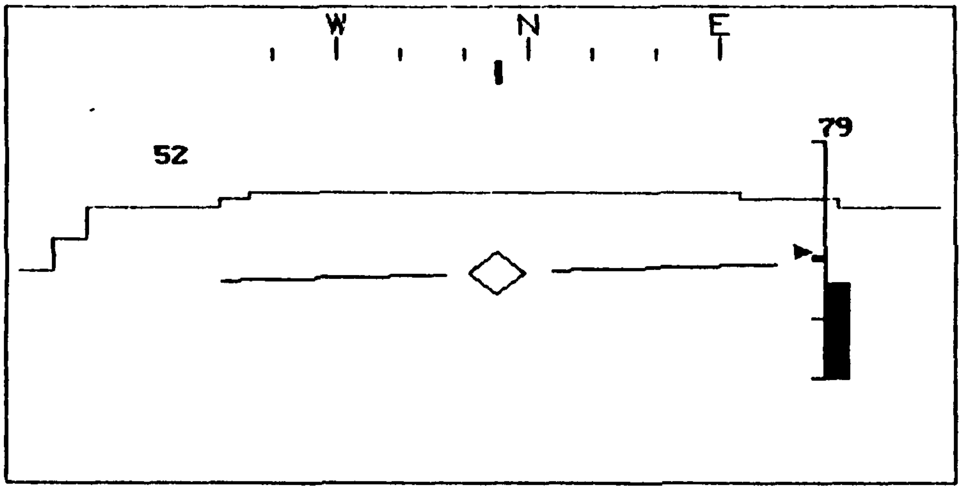
20



BES Engineering Services

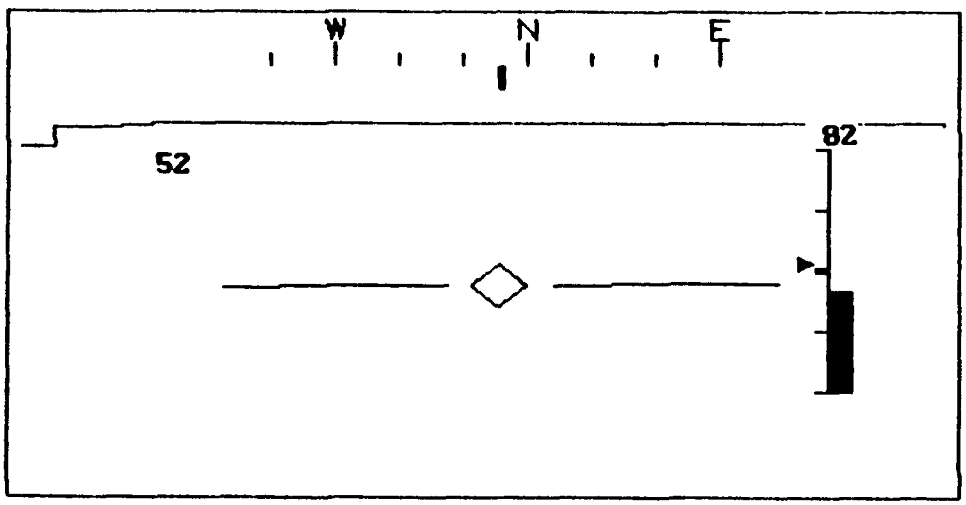
4

FLIGHT 861



BES Engineering Services

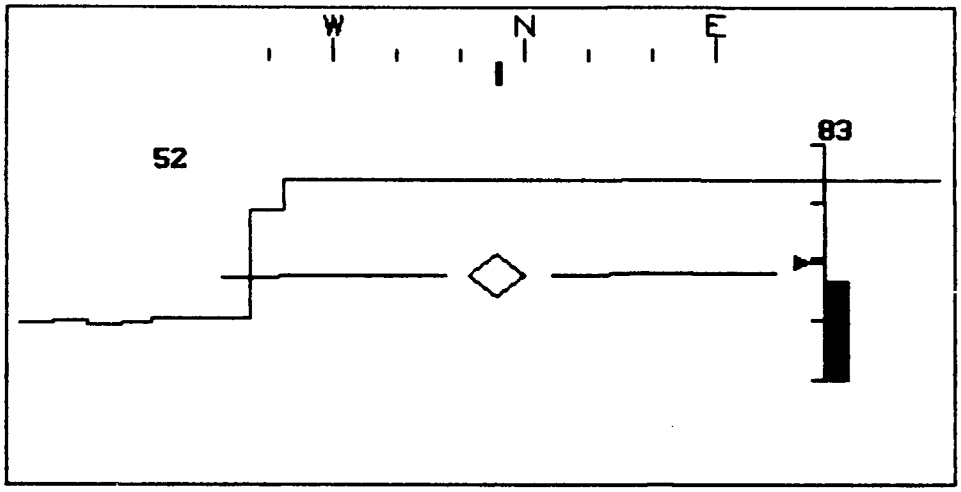
6



BES Engineering Services

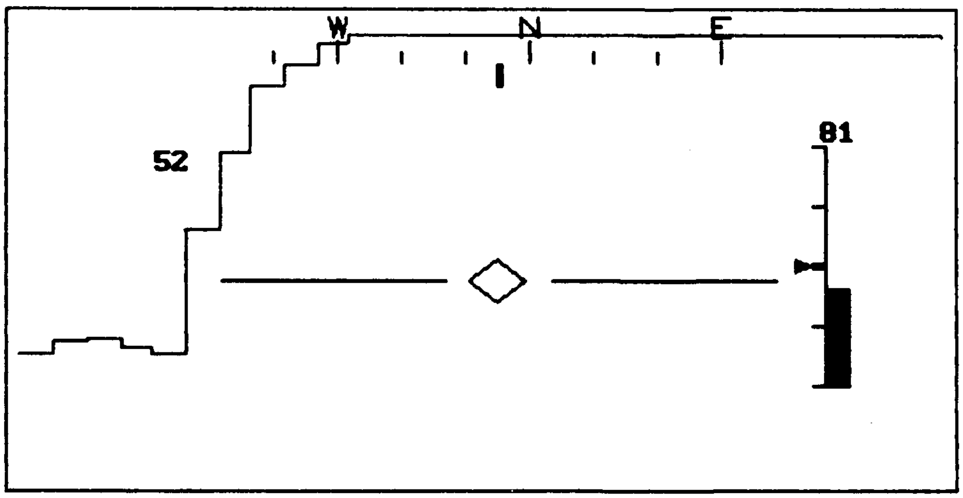
4

FLIGHT 861



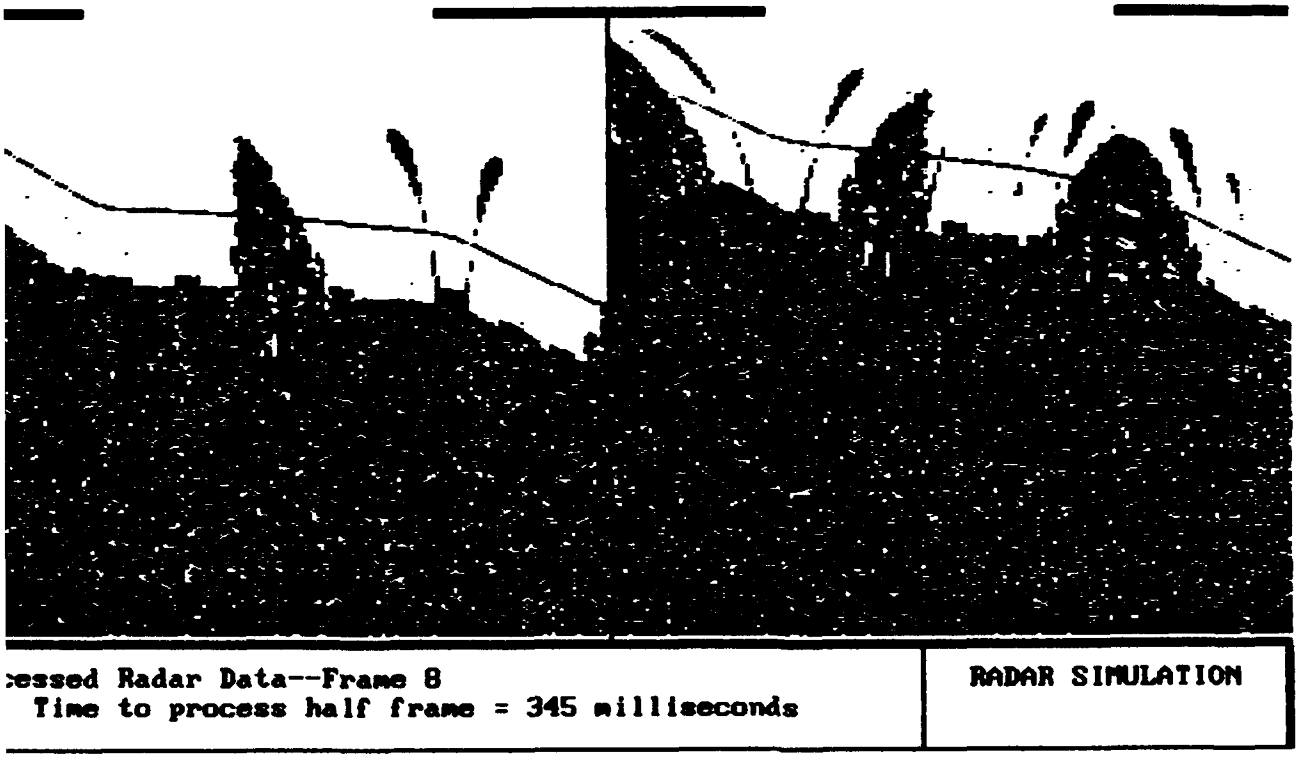
BES Engineering Services

6



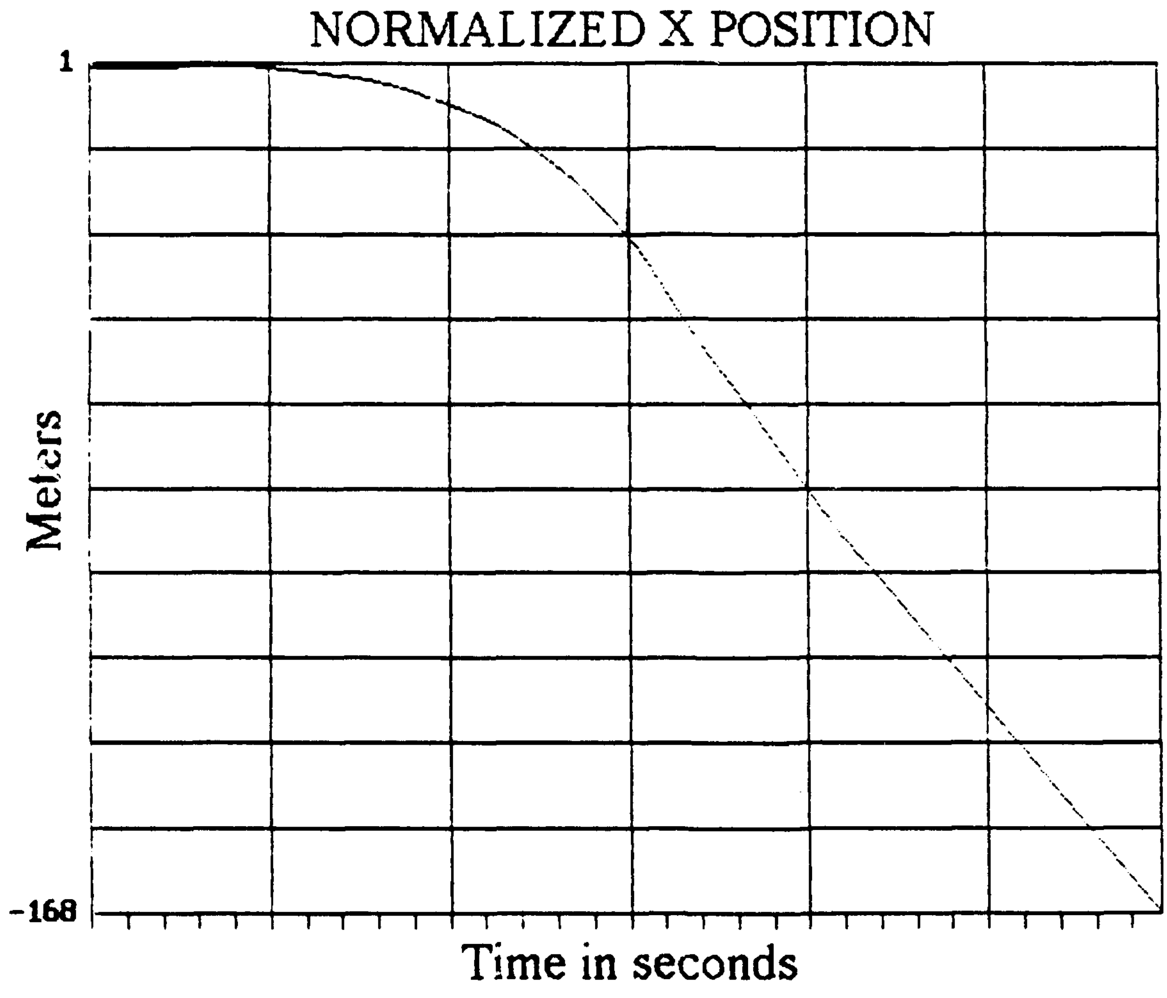
BES Engineering Services

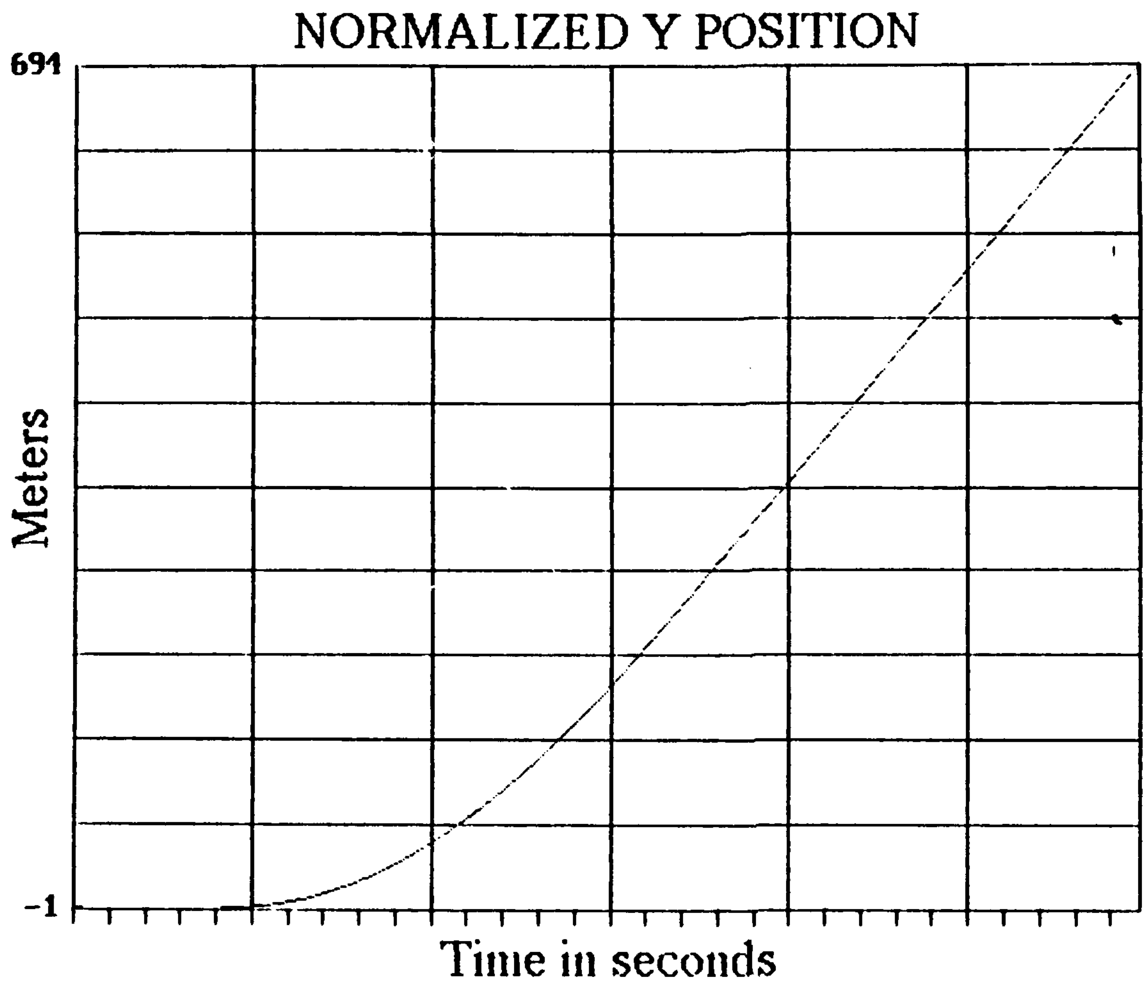
FLIGHT 853

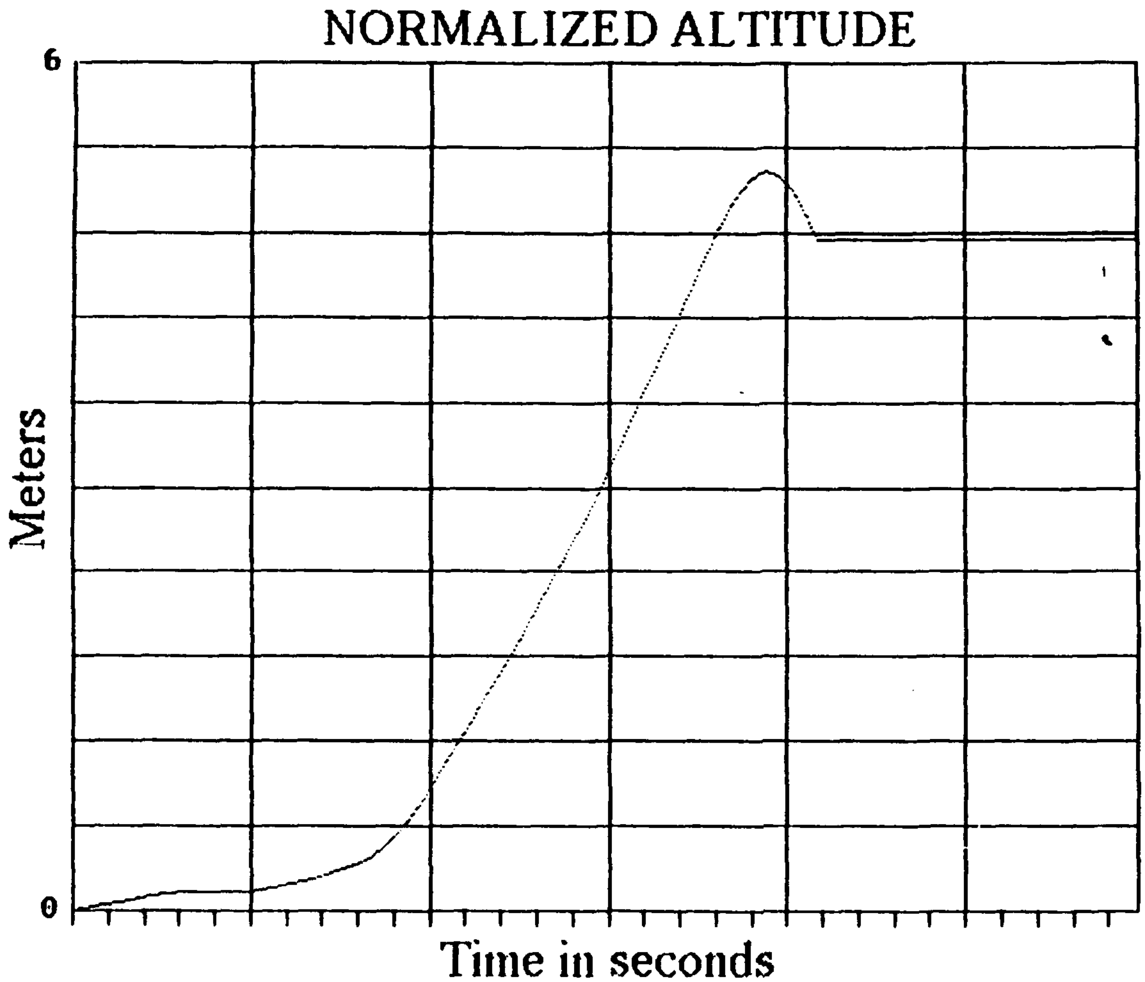

cessed Radar Data--Frame 8
Time to process half frame = 345 milliseconds
RADAR SIMULATION

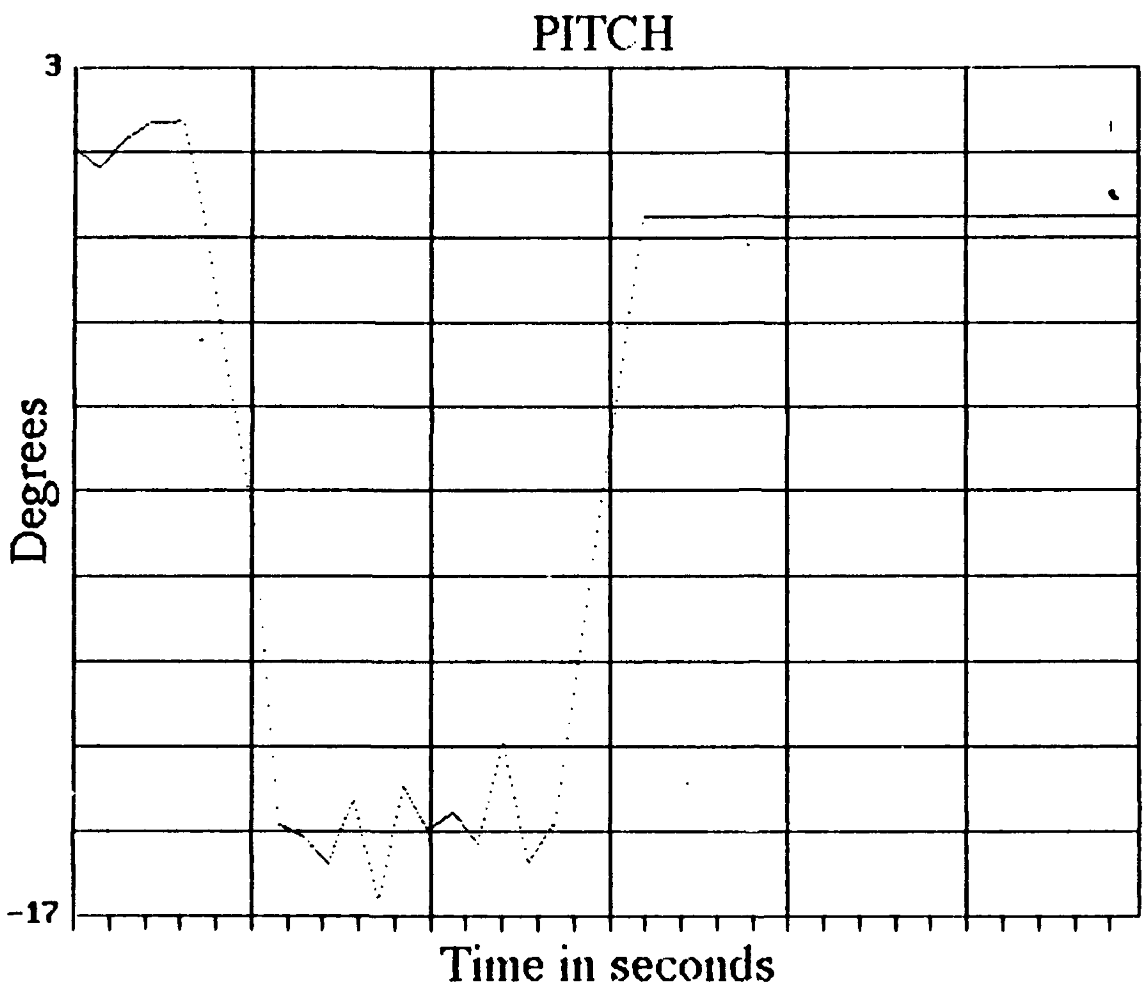
APPENDIX F

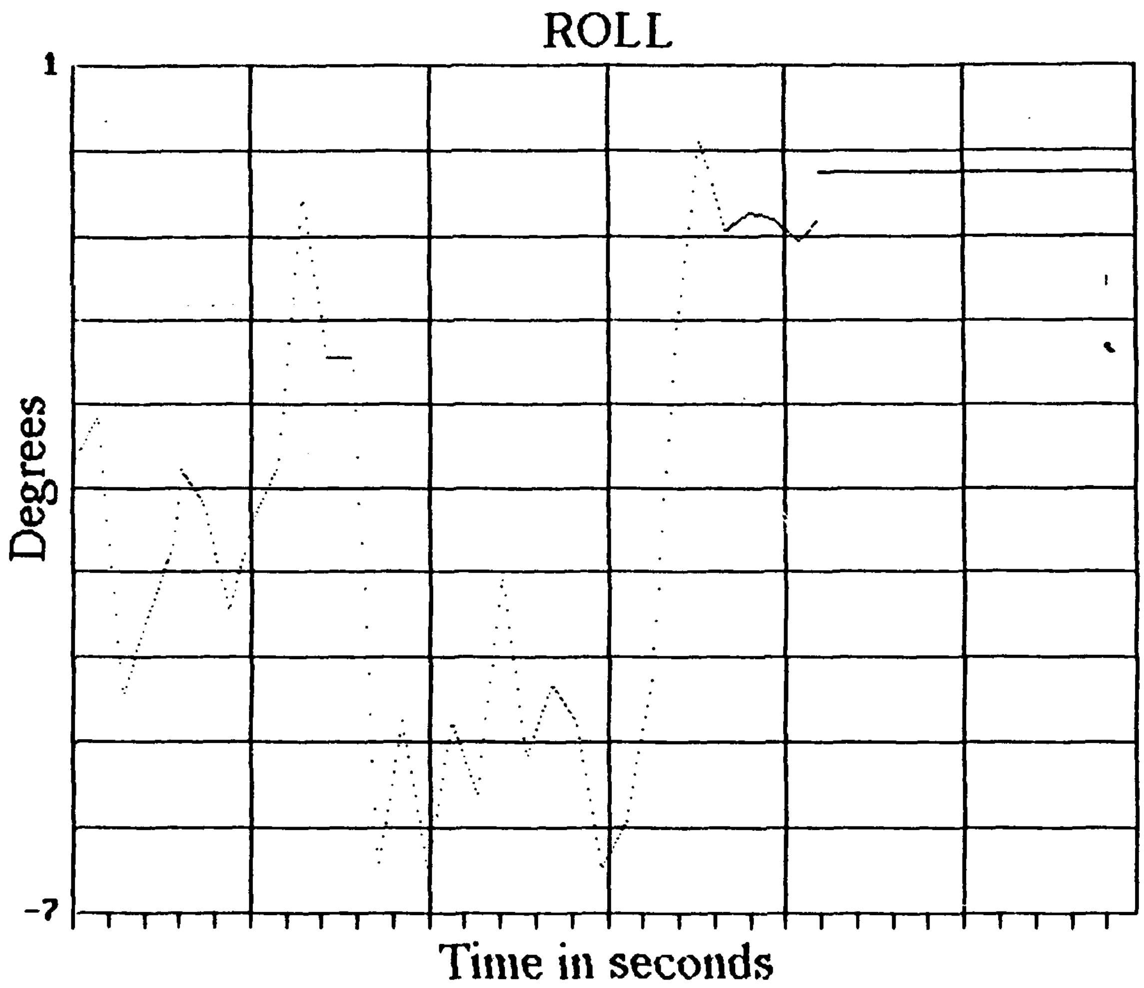
FLIGHT 854/862 TIME HISTORY PLOTS

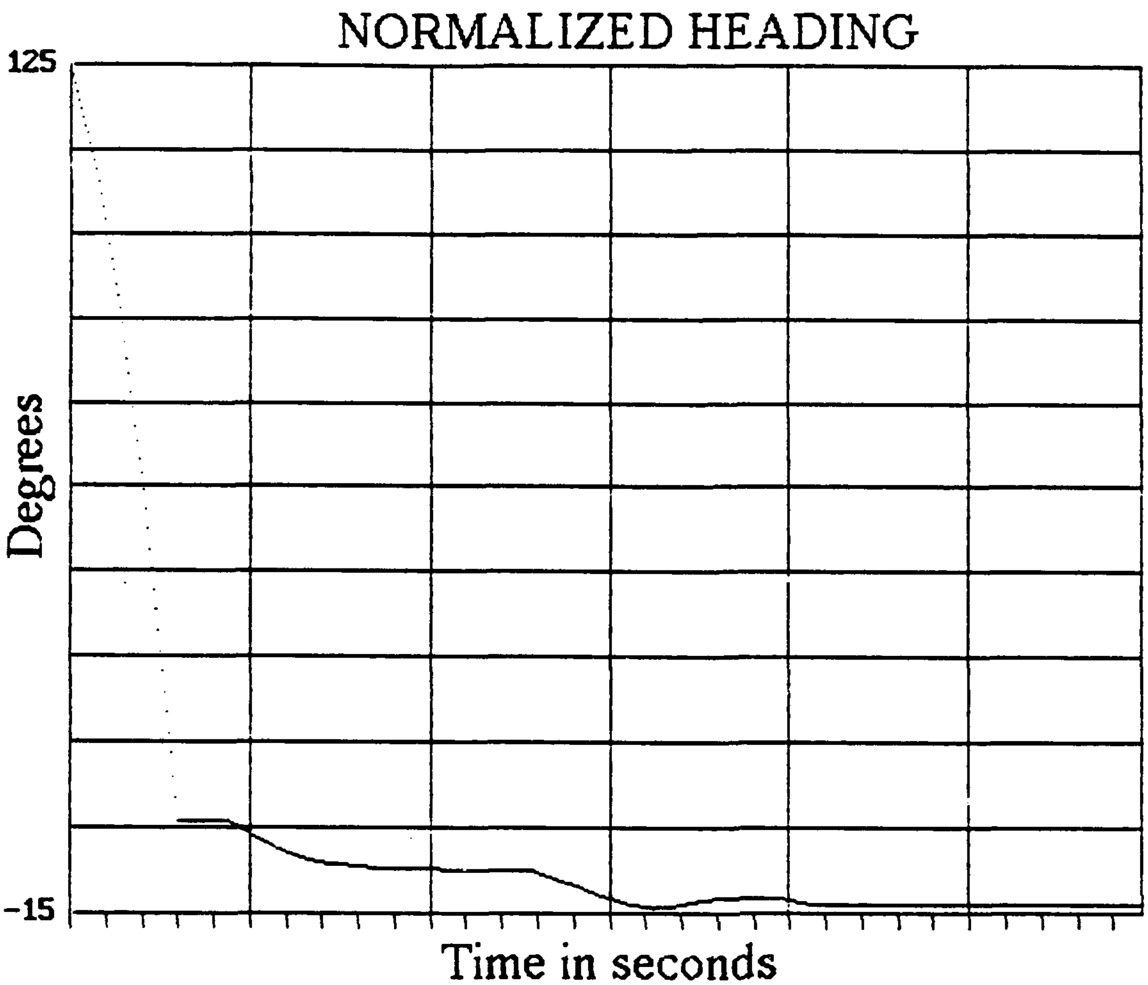


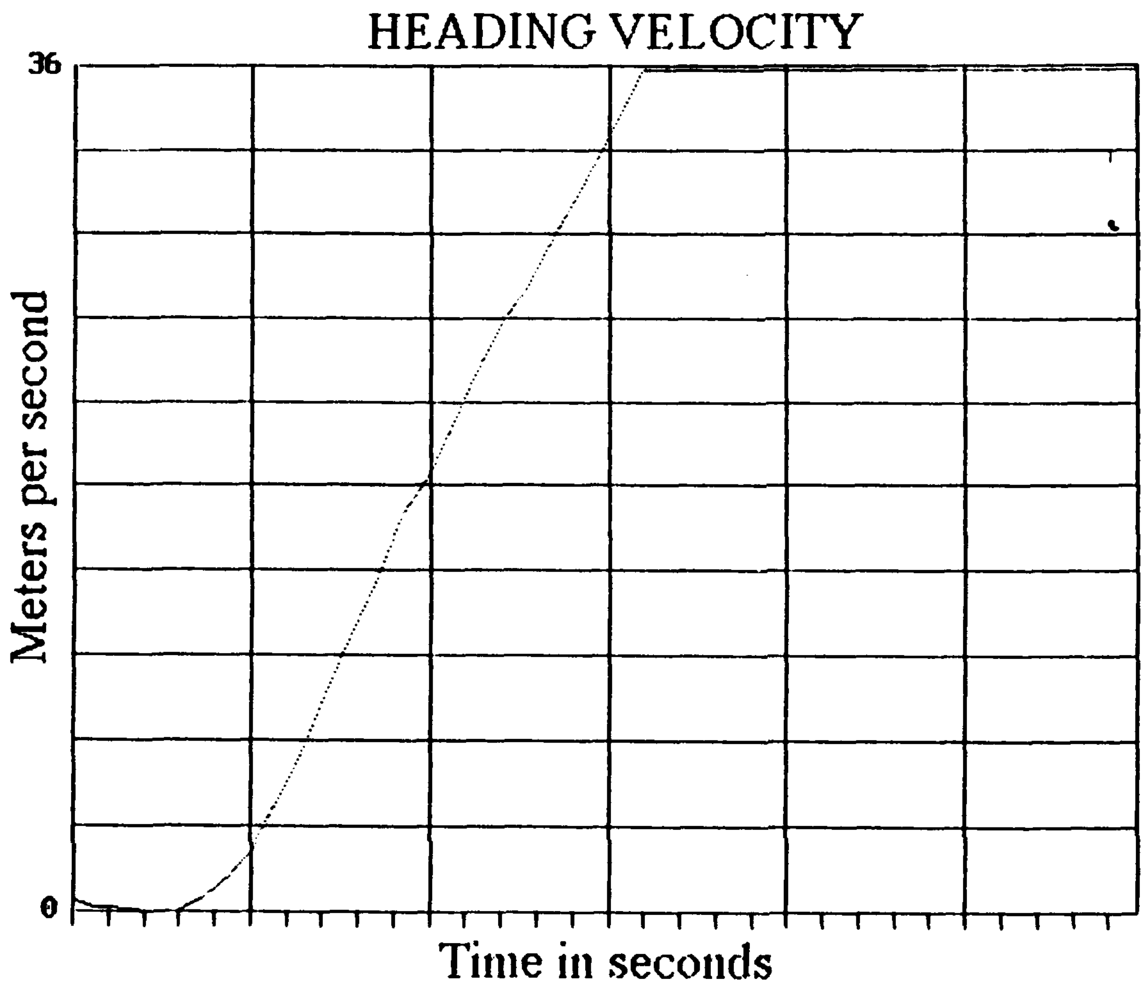

NORMALIZED Y POSITION
691
-1
Meters
Time in seconds

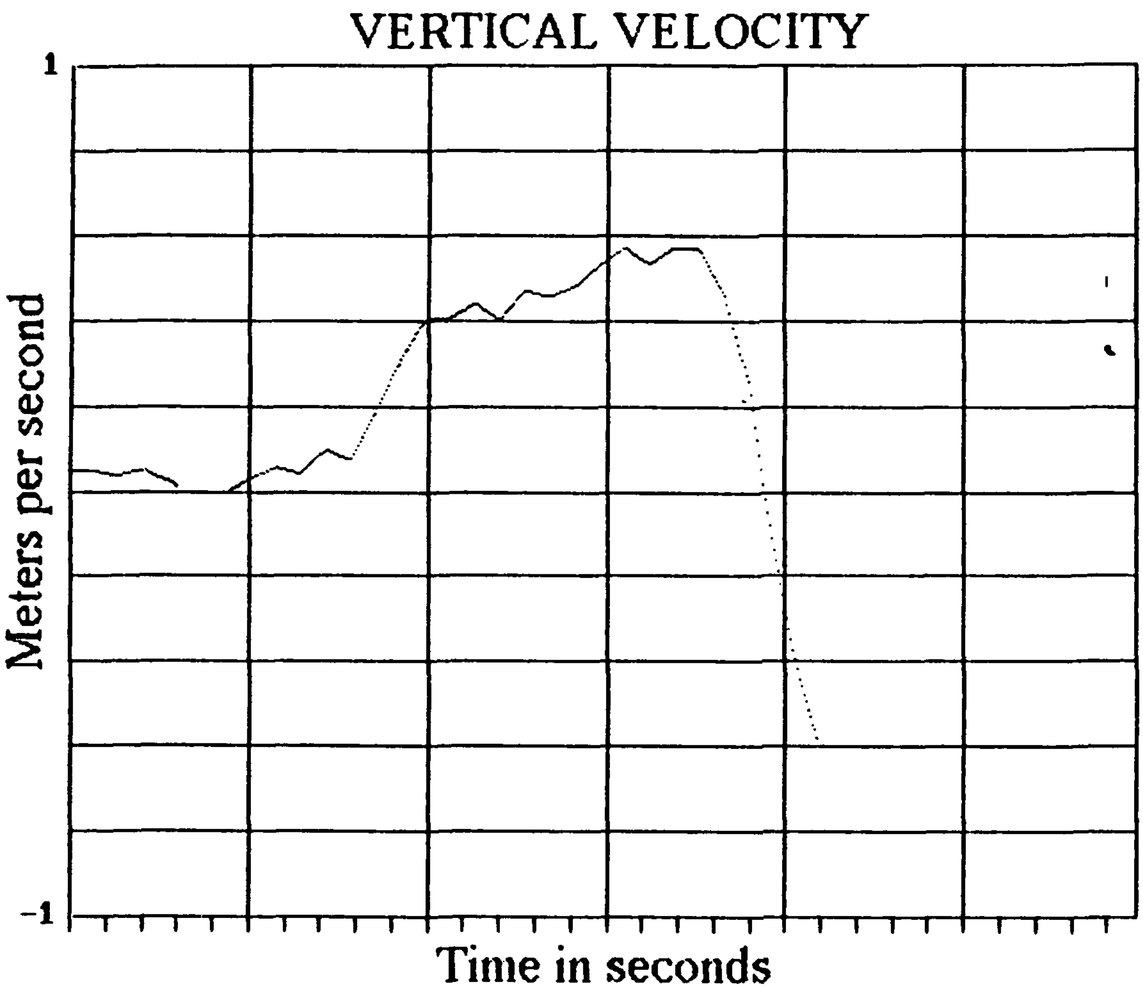

NORMALIZED ALTITUDE
6
0
Meters
Time in seconds

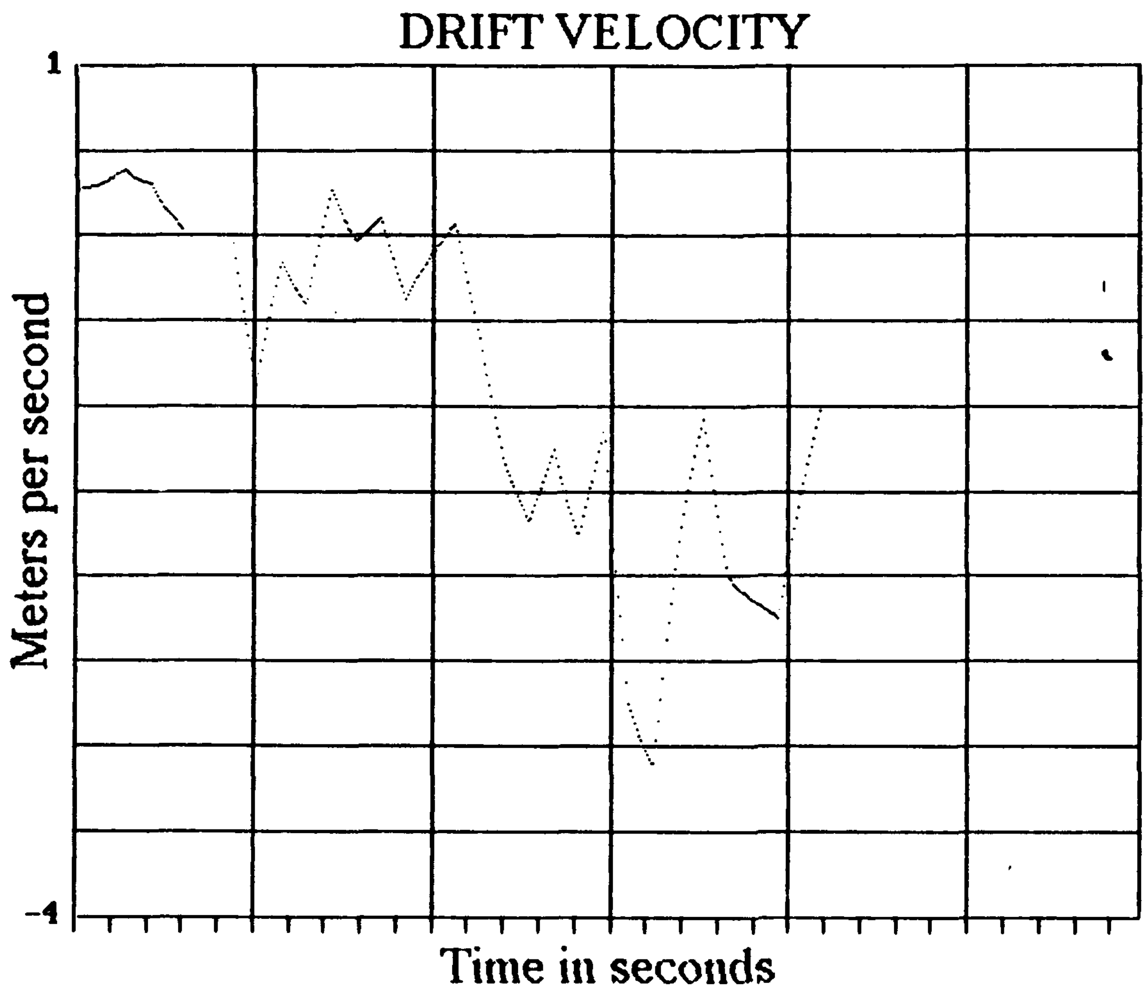

PITCH
3
-17
Degrees
Time in seconds


ROLL
1
-7
Degrees
Time in seconds


NORMALIZED HEADING
125
-15
Degrees
Time in seconds


HEADING VELOCITY
36
0
Meters per second
Time in seconds


VERTICAL VELOCITY
1
-1
Meters per second
Time in seconds

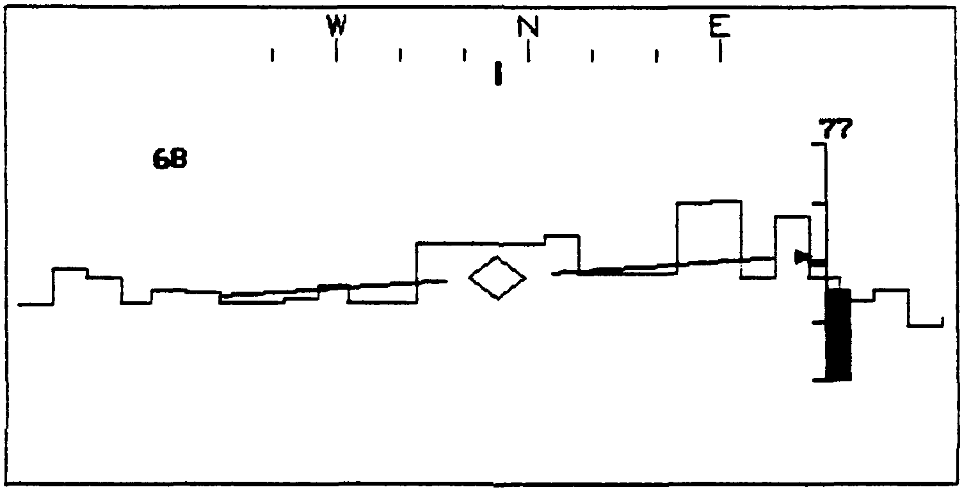

DRIFT VELOCITY
1
-4
Meters per second
Time in seconds

APPENDIX G

SELECTED WOS DISPLAYS AND RADAR PLOTS FOR FLIGHT 854/862

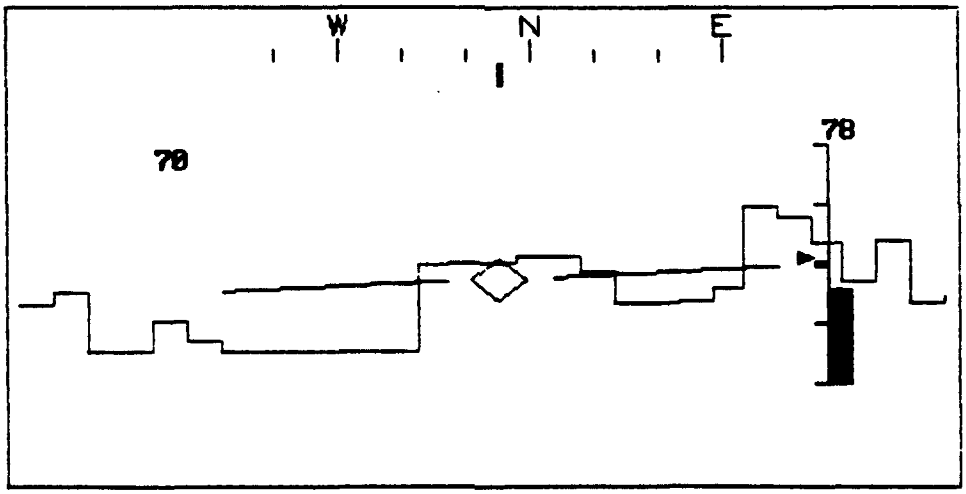
11 10

FLIGHT 854



BES Engineering Services

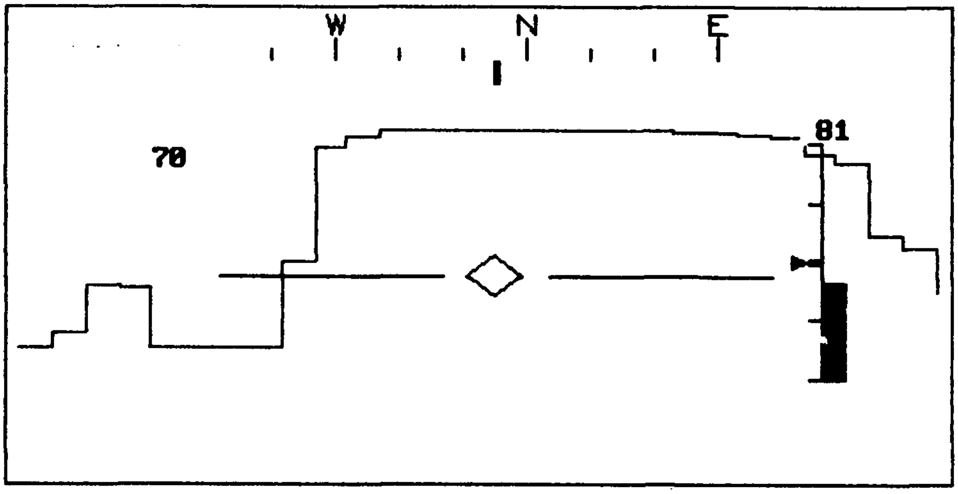
12 1



BES Engineering Services

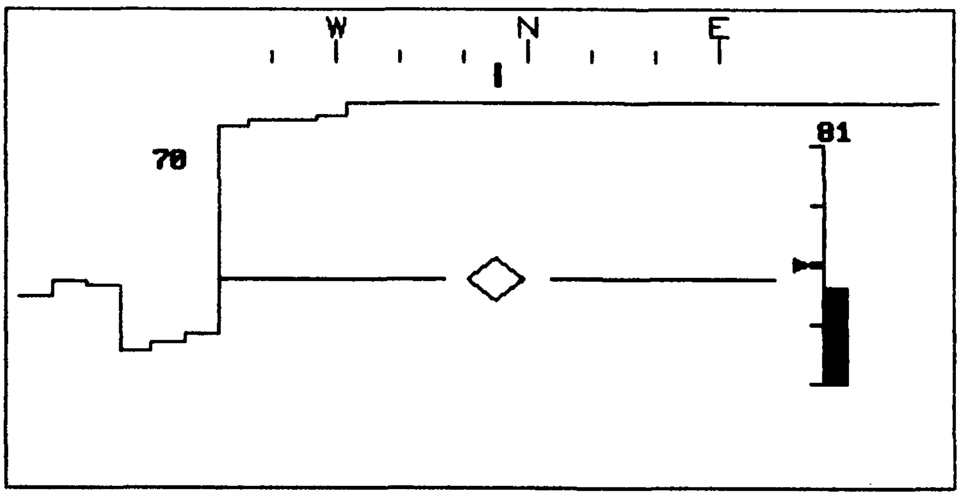
1

FLIGHT 854



BES Engineering Services

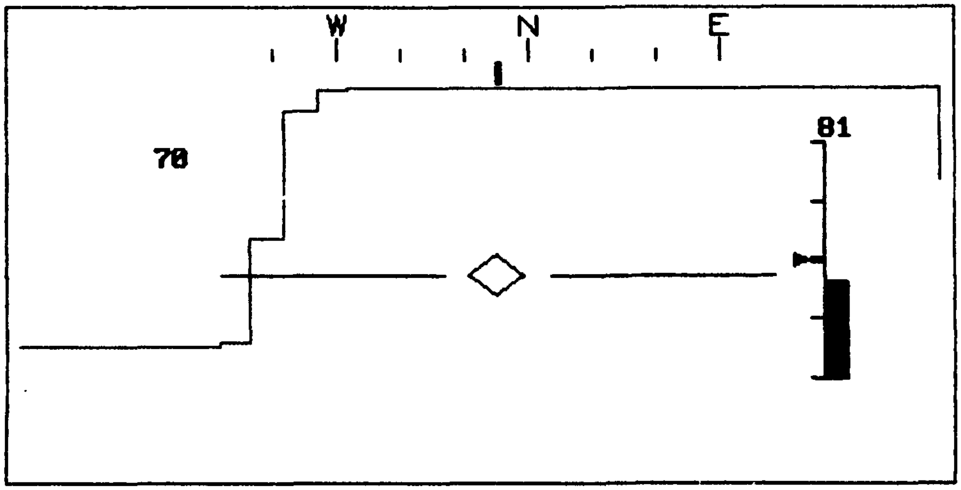
14



BES Engineering Services

7 2

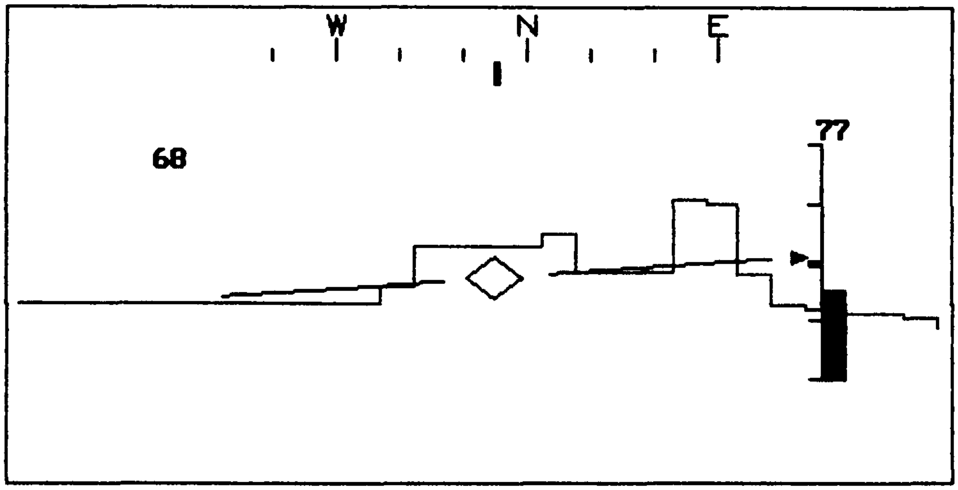
FLIGHT 854



BES Engineering Services

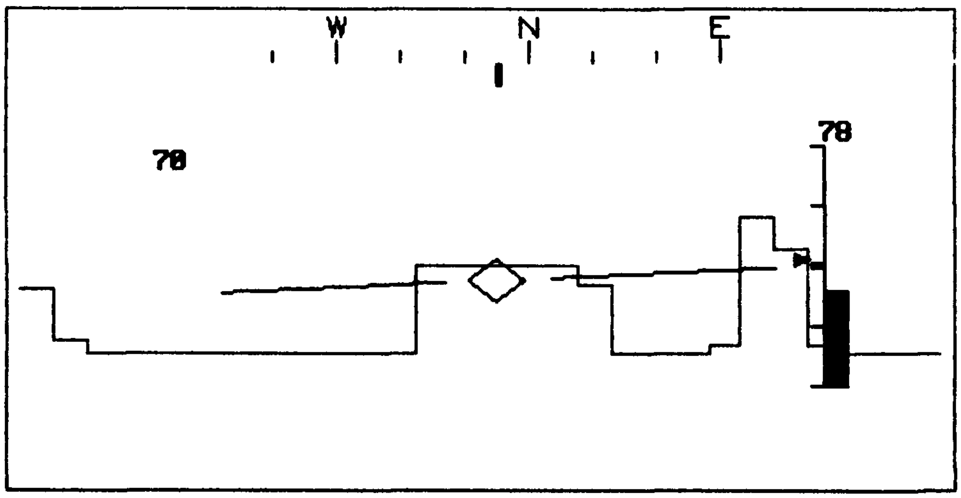
10

FLIGHT 862



BES Engineering Services

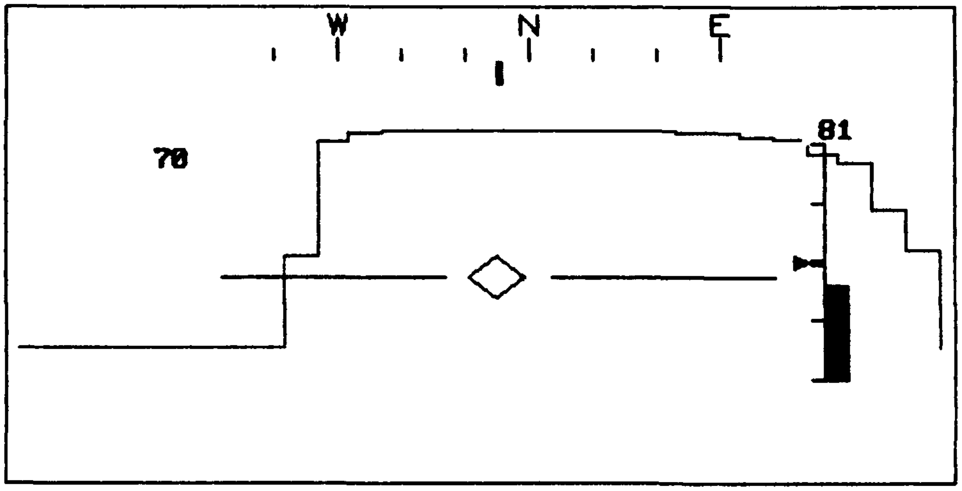
1



BES Engineering Services

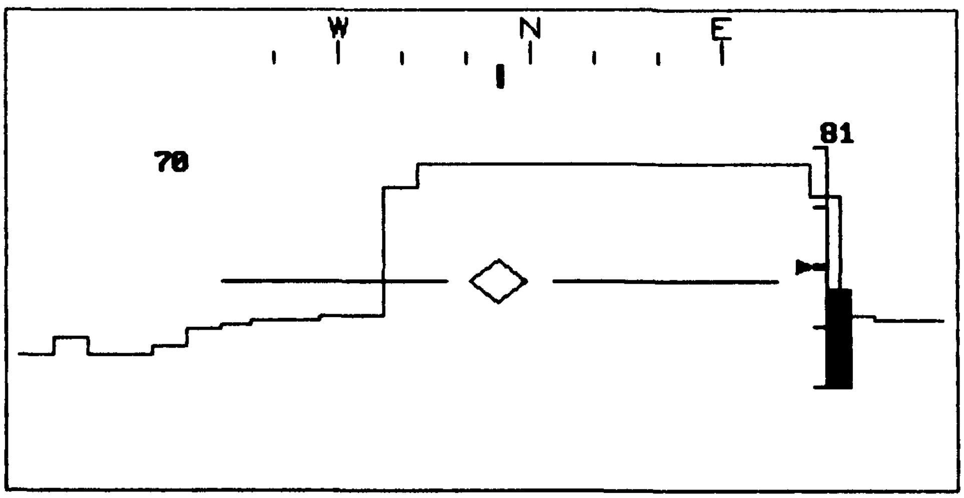
1

FLIGHT 862



BES Engineering Services

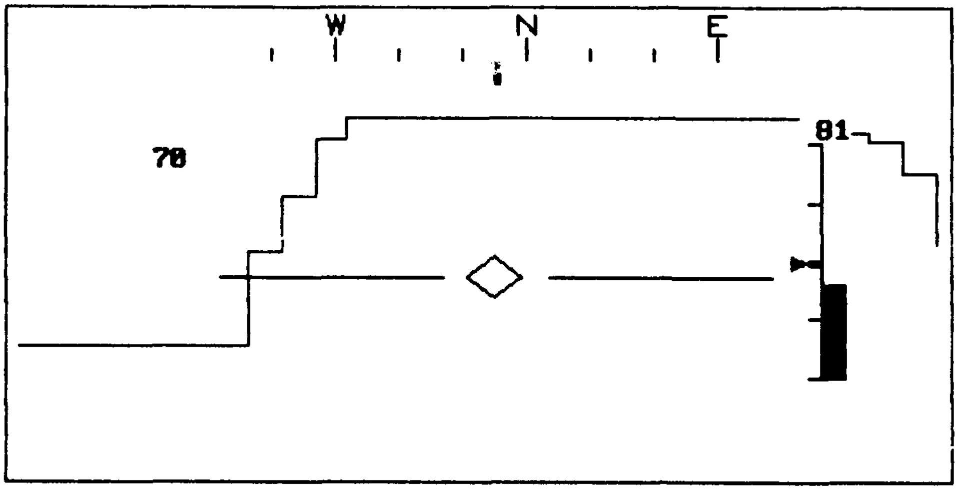
14



BES Engineering Services

2

FLIGHT 862



BES Engineering Services

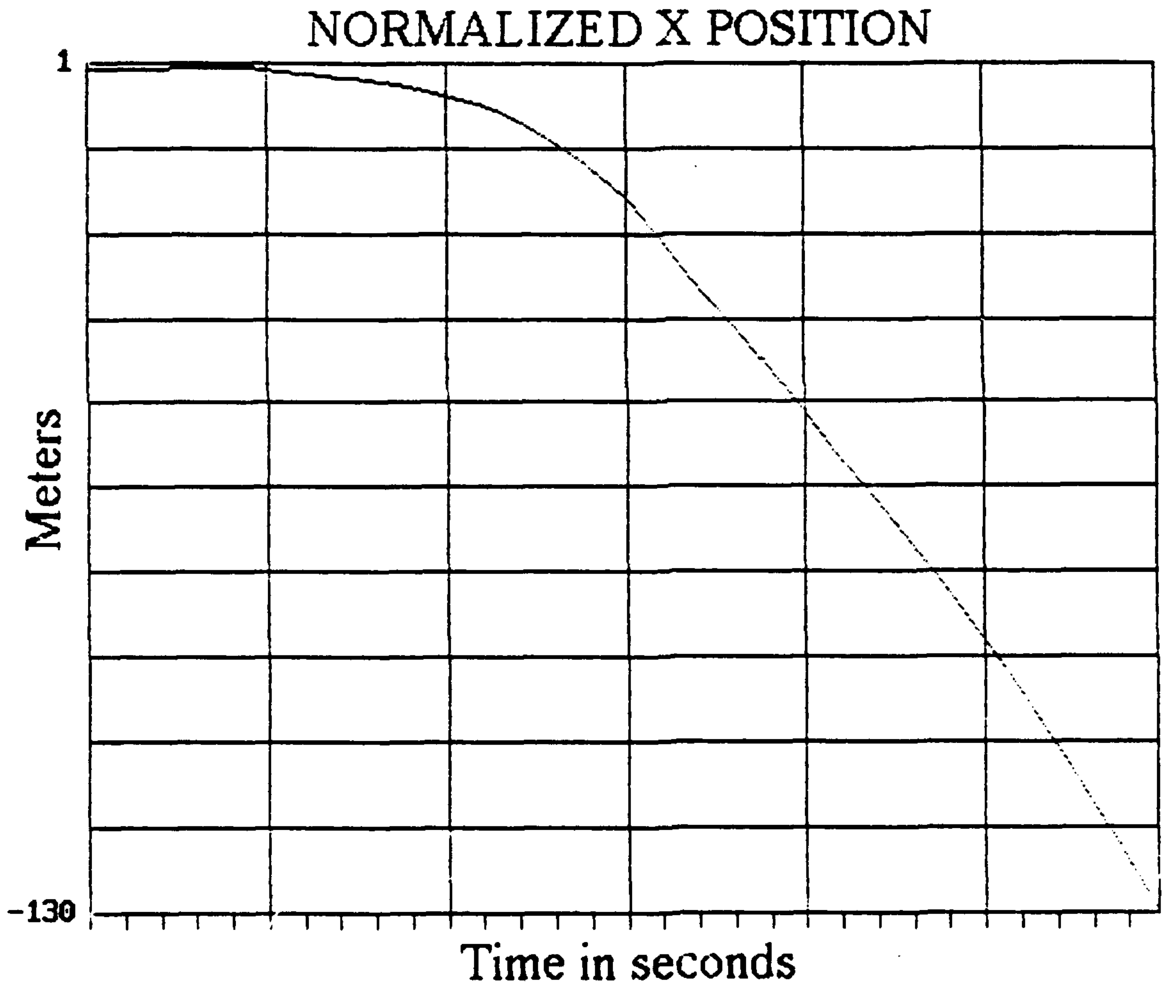
FLIGHT 854

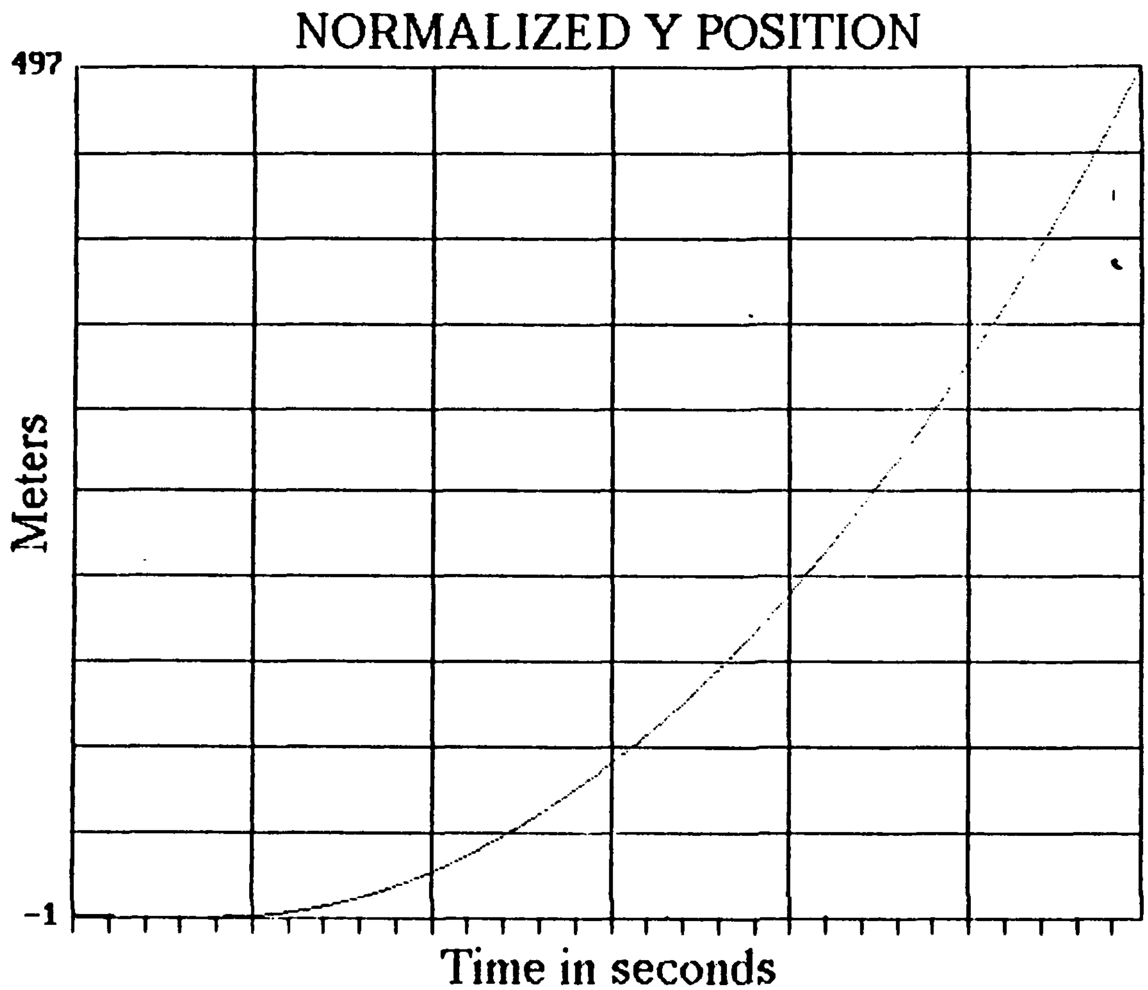
Processed Radar Data--Frame 10
Time to process half frame = 305 milliseconds

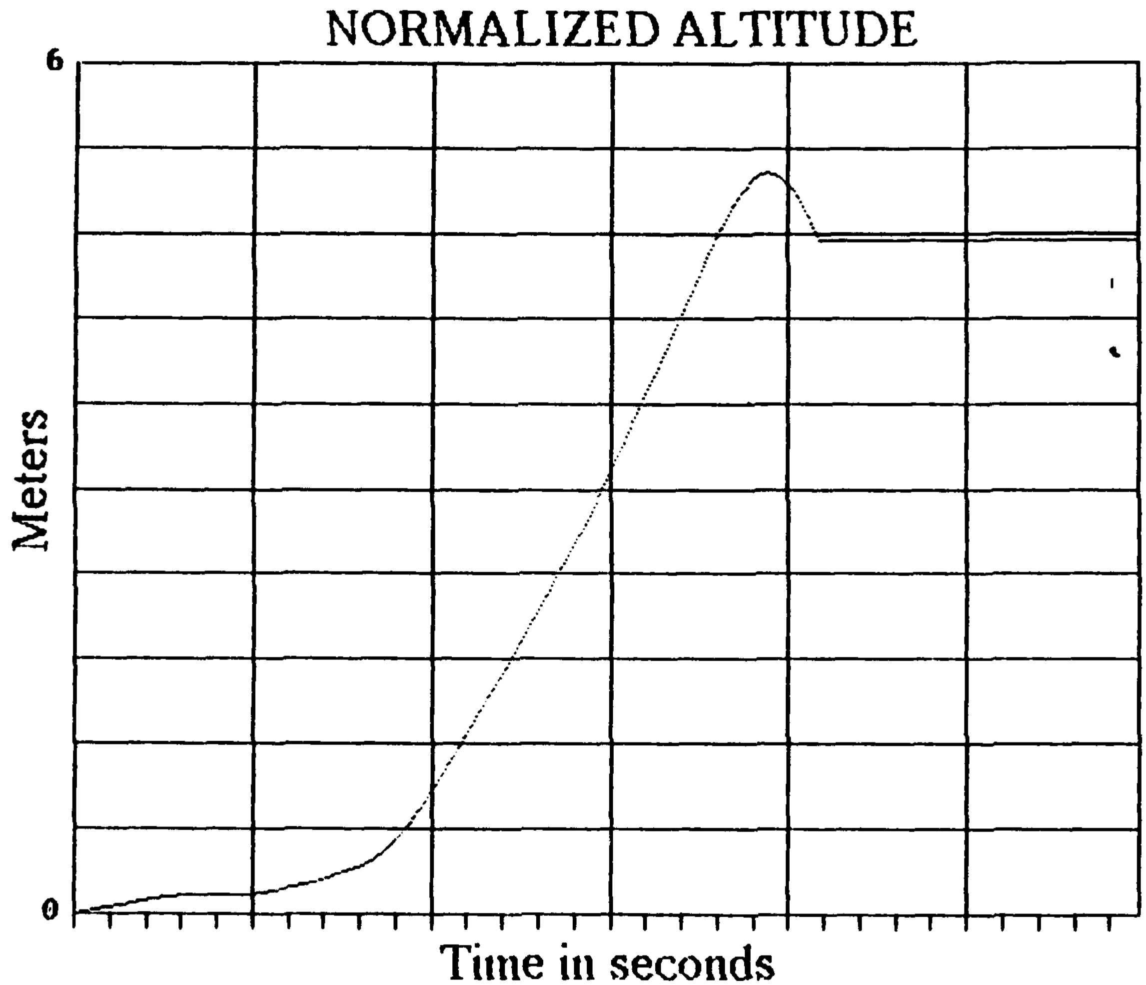
RADAR SIMULATION

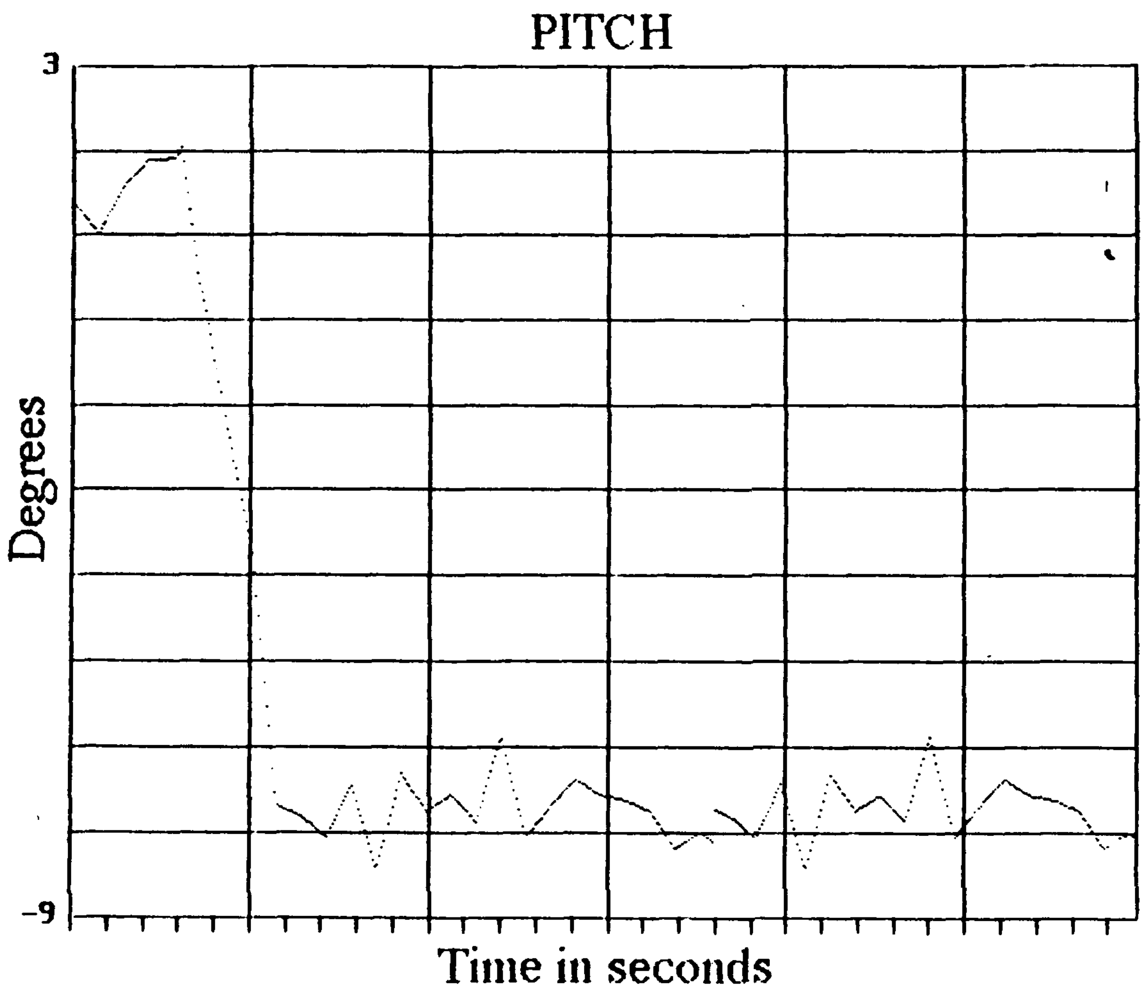
APPENDIX H

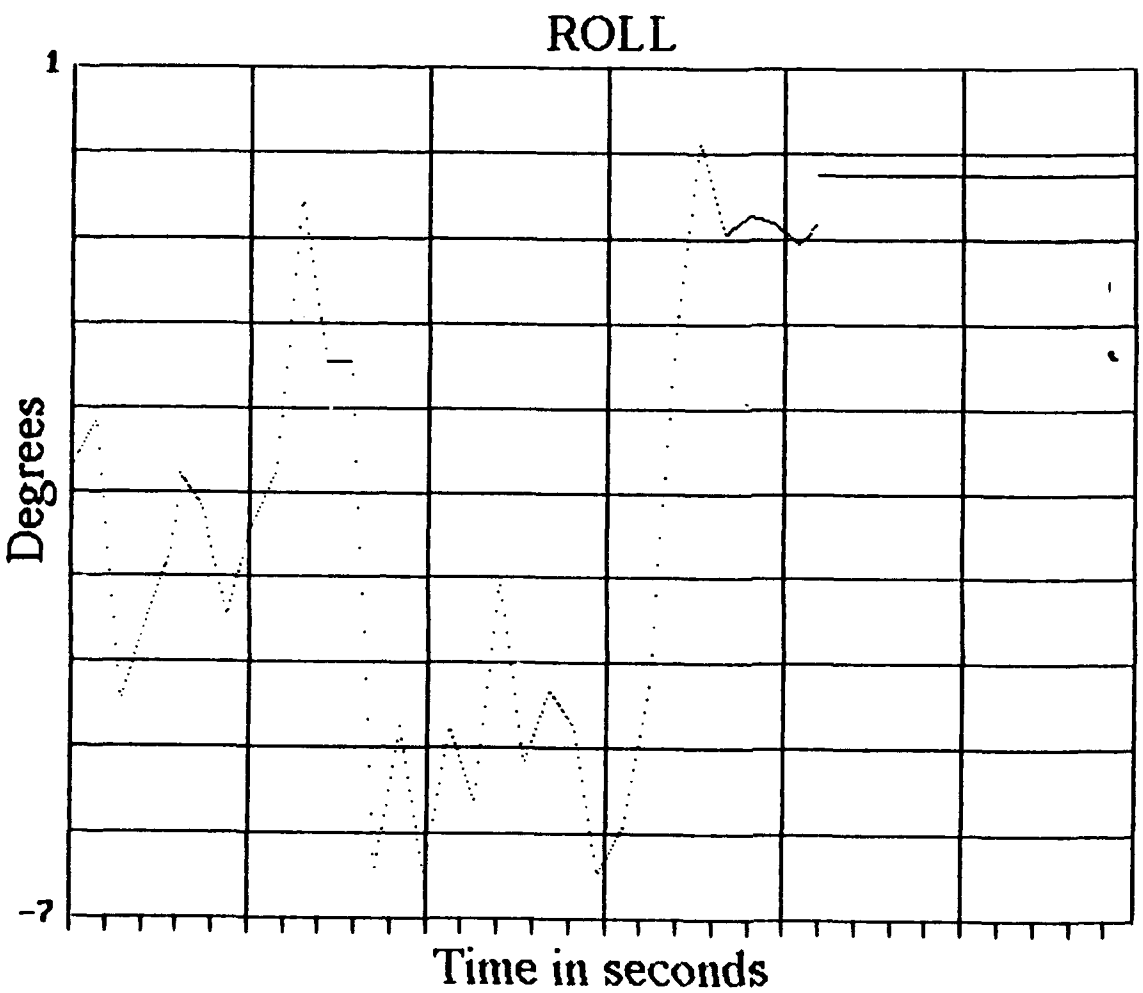
FLIGHT 855/863 TIME HISTORY PLOTS

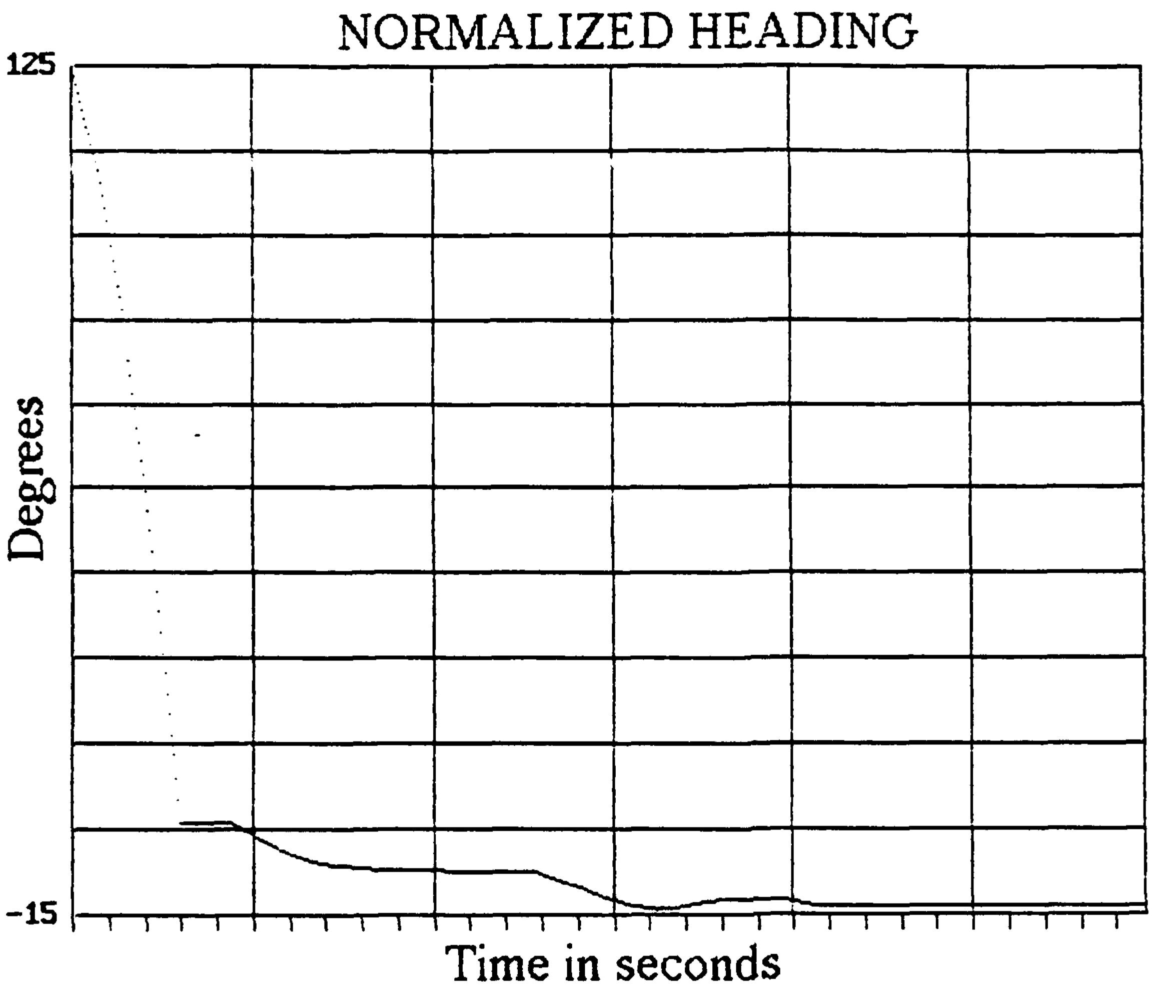


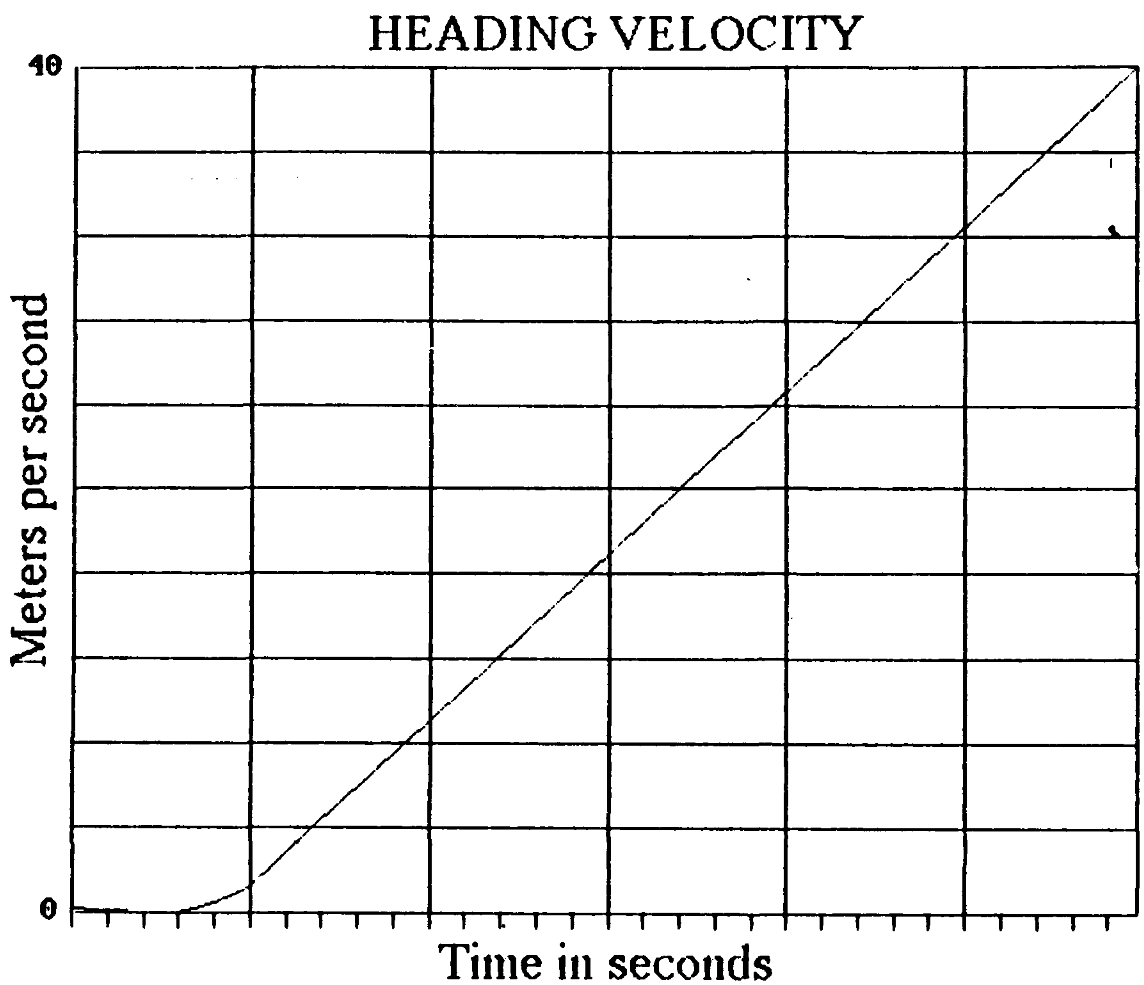

NORMALIZED Y POSITION
497
-1
Meters
Time in seconds

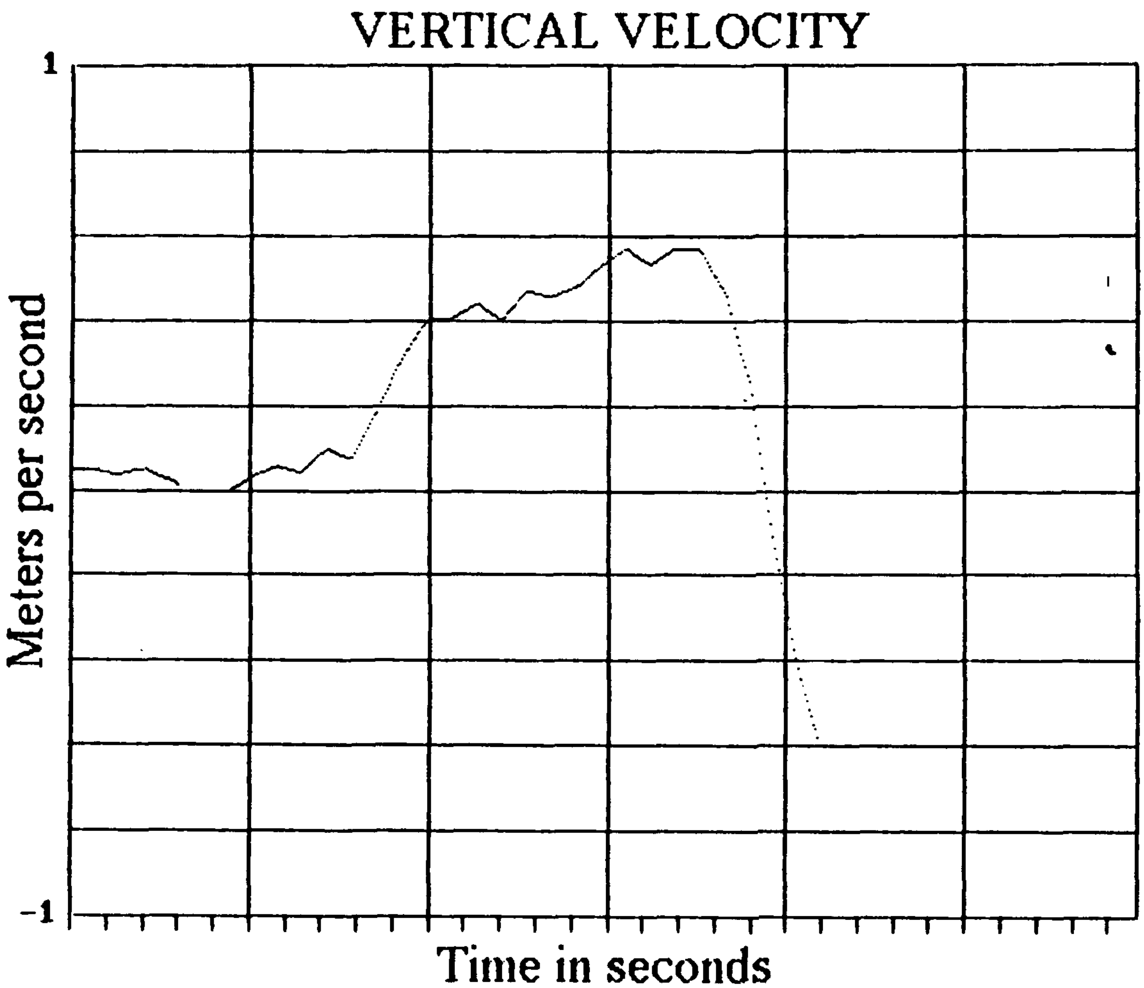

NORMALIZED ALTITUDE
6
0
Meters
Time in seconds

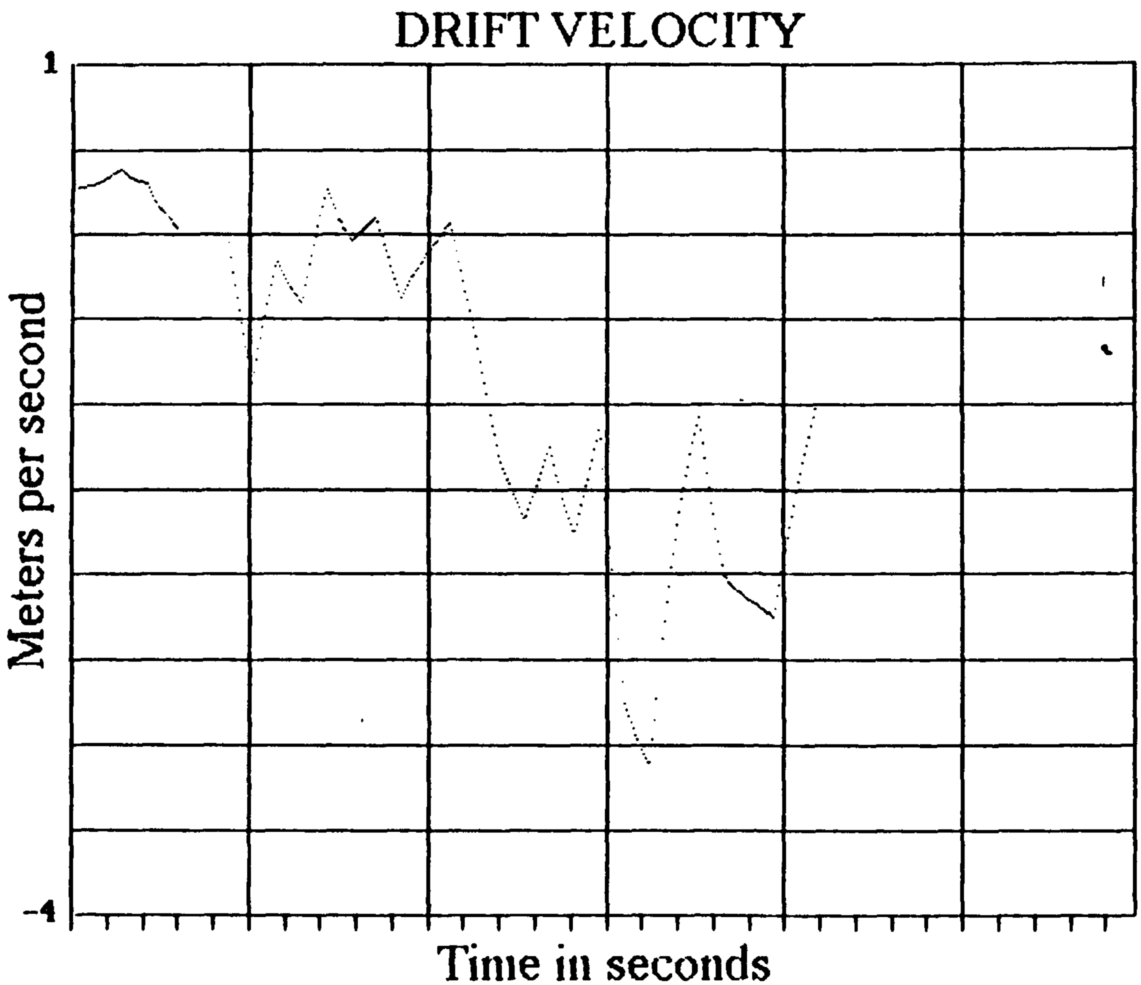

PITCH
3
Degrees
-9
Time in seconds


ROLL
1
-7
Degrees
Time in seconds


NORMALIZED HEADING
125
-15
Degrees
Time in seconds


HEADING VELOCITY
40
0
Meters per second
Time in seconds


VERTICAL VELOCITY
1
-1
Meters per second
Time in seconds

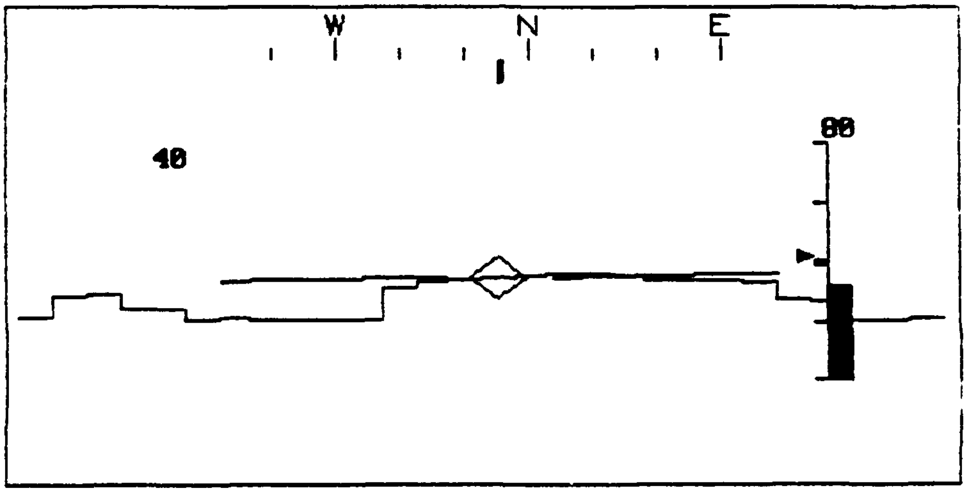

DRIFT VELOCITY
1
-4
Meters per second
Time in seconds

APPENDIX I

SELECTED WOS DISPLAYS AND RADAR PLOTS FOR FLIGHT 855/863

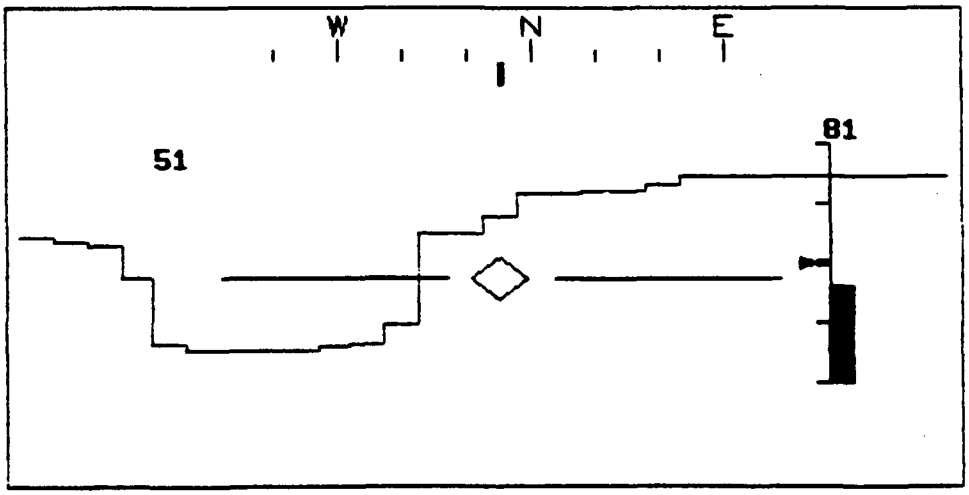
12 10

FLIGHT 855



BES Engineering Services

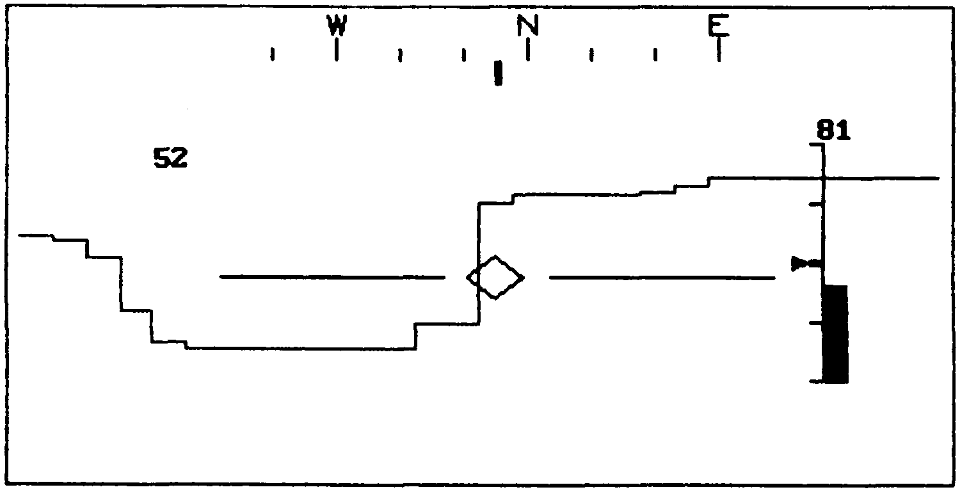
15 1



BES Engineering Services

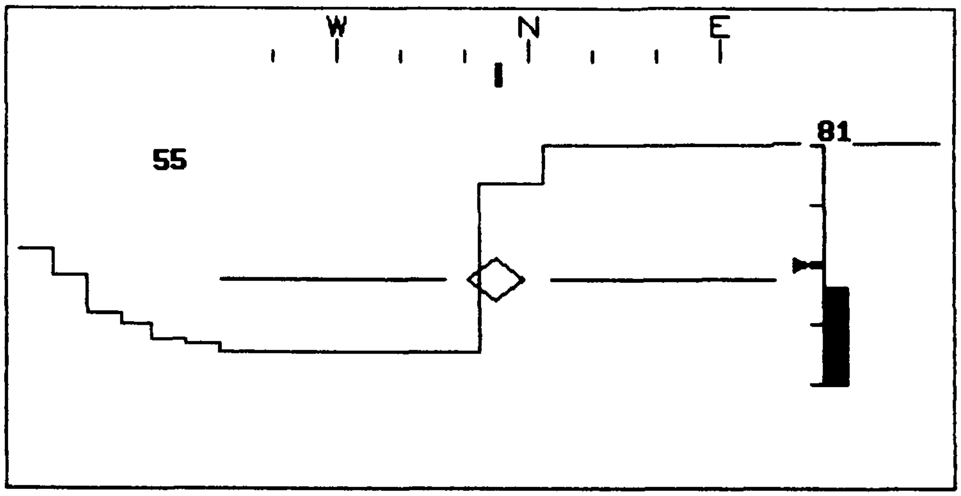
5 4

FLIGHT 855



BES Engineering Services

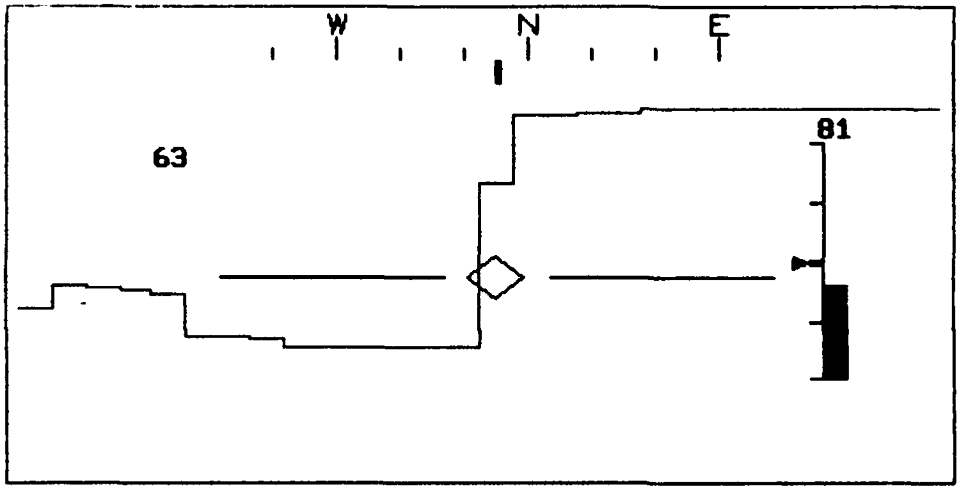
5 18



BES Engineering Services

12

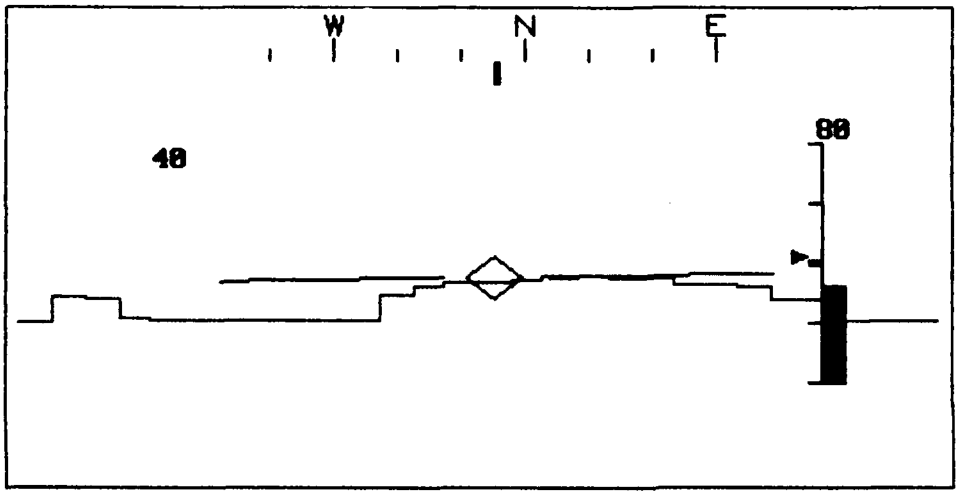
FLIGHT 855



BES Engineering Services

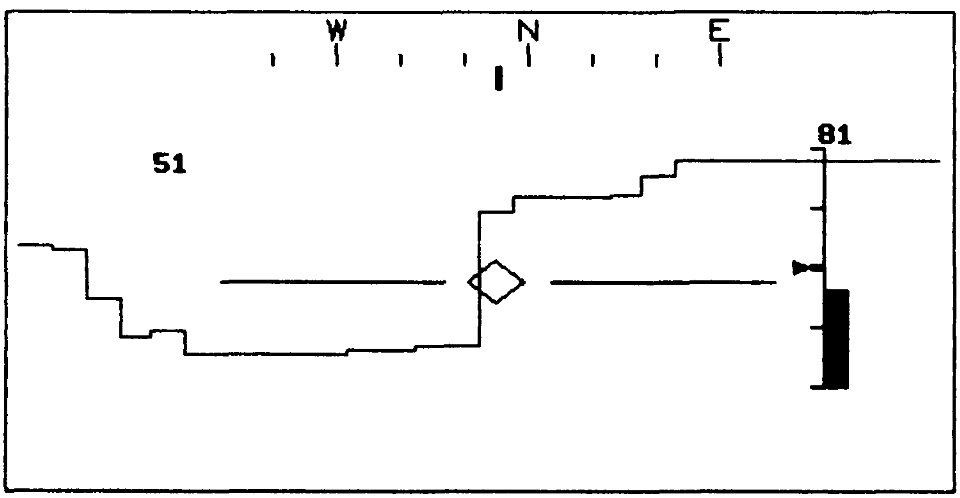
10

FLIGHT 863



BES Engineering Services

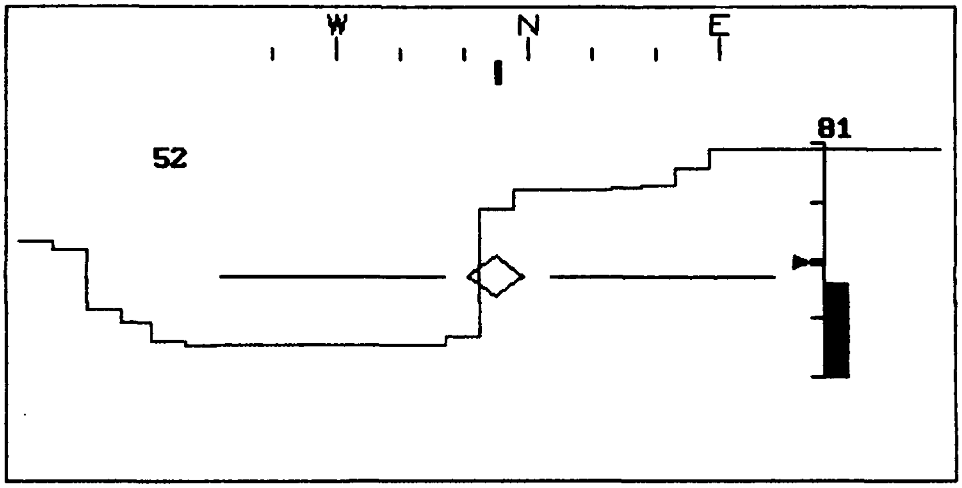
1



BES Engineering Services

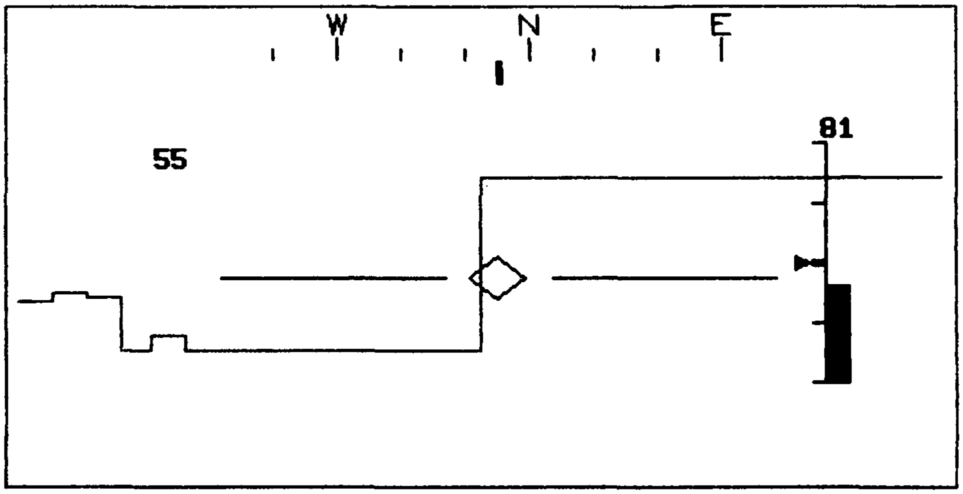
15 4

FLIGHT 863



BES Engineering Services

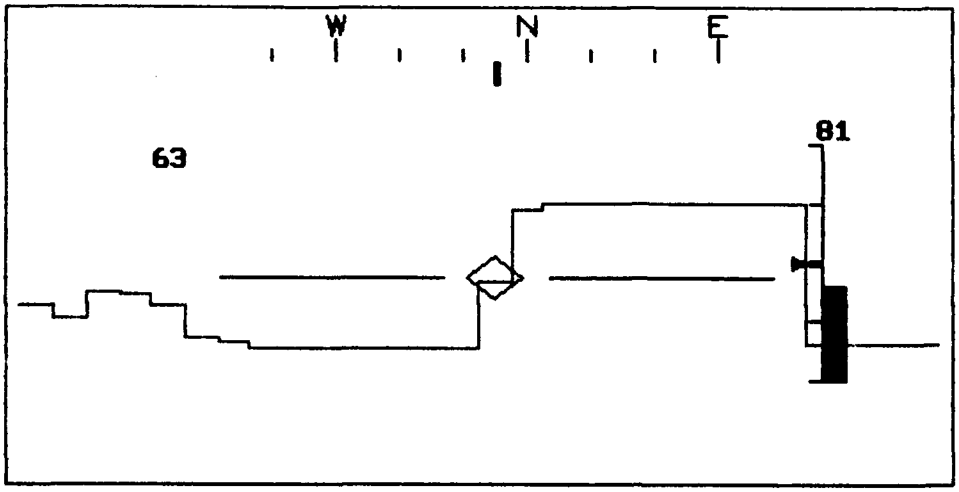
15 18



BES Engineering Services

17 12

FLIGHT 863



BES Engineering Services

FLIGHT 855

Processed Radar Data--Frame 7 Time to process half frame = 340 milliseconds	RADAR SIMULATION

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